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**Tesi di Laurea Magistrale**

# How the Cislunar Station can support refueling of a high-power electric spacecraft for Moon-Mars cargo transfers

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# How the Cislunar Station can support refueling of a high-power electric spacecraft for Moon-Mars cargo transfers

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# Acknowledgements

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# List of Acronyms

| | |
|---|---|
| AOCS | Attitude and Orbit Control Subsystem |
| ConOps | Concept of Operations |
| CP | Chemical Propulsion |
| DMS | Data Management Subsystem |
| DRA | Design Reference Architecture |
| DRM | Design Reference Mission |
| EOL | End-of-Life |
| EOR | Electric Orbit Raising |
| EP | Electric Propulsion |
| EPS | Electrical Power Subsystem |
| FoM | Figure of Merit |
| HARN | Harness Subsystem |
| HET | Hall-Effect Thruster |
| I/F | Interface |
| ICV | Interplanetary Cargo Vehicle |
| LEO | Low Earth Orbit |
| LEOP | Launch and Early Orbit Phase |
| LOP-G | Lunar Orbital Platform-Gateway |
| MBC | Mars Base Camp |

| | |
|---|---|
| MDPS | Meteoroid/Debris Protection System |
| MMOD | Micrometeoroids and Orbital Debris |
| MoO | Mode of Operations |
| MOS | Mars Orbital Station |
| MTV | Mars Transfer Vehicle |
| NEAs | Near-Earth Asteroids |
| OBC | On-Board Computer |
| PBD | Phases Block Diagram |
| PCDU | Power Conditioning and Distribution Unit |
| PPE | Power an Propulsion Element |
| PPU | Power Processing Unit |
| PROP | Propulsion Subsystem |
| REF | Refueling Subsystem |
| RIU | Remote Interface Unit |
| S&M | Structures and Mechanisms Subsystem |
| SEP | Solar Electric Propulsion |
| TBD | To be defined |
| TCS | Thermal Control Subsystem |
| TT&C | Tracking Telemetry and Command Subsystem |

# Abstract

The thesis work deals with the analysis of Moon-Mars cargo transfers scenarios with the aim of supporting a future Mars orbital station. The presence of a Mars outpost poses the issue of its maintenance and sustainment: for these purposes, an electric space tug could be involved in cargo transportation missions. The scenarios describe the transfer of a multi-tons Cargo Module from the Near-Rectilinear Halo Orbit to 1-sol Mars Orbit, and vice versa. To support multiple transfers, dedicated refueling operations at Lunar Orbital Platform-Gateway are envisaged. The thesis work starts from an overview of the possible transportation mission concepts exploiting high-power solar electric propulsion; a brief system and mission analysis methodology is introduced. Then it focuses on the detailed definition of the mission objectives and constraints, and on the functional analyses at various levels. The most important results of these analyses are the functional architecture and the physical block diagram. The thesis work continues with the description of the Concept of Operations, from the mission phases analyses to the Modes of Operations definition, through an iterative refinement process. The overall mission scenarios have been derived from trade-off analyses that have been performed to choose the mission architecture that, most of all, cost-effectively satisfy stakeholder expectations. The most important features of these analyses and their results are described within the study. Eventually, in the last part of the study main conclusions are drawn on the selected mission scenarios.

# Chapter 1

# Transportation Mission Concepts exploiting Solar Electric Propulsion

## 1.1 Introduction

Sustainable access to space is necessary to advance human exploration capabilities. There is therefore a growing interest in the development of innovative transportation vehicles, that could implement an efficient and cost-effective method of transporting mass in space. The sustained exploration of the Solar system, including ambitious projects aimed at Moon and Mars, requires advances in multiple areas spanning nearly every aspect of space technology.

Among these technologies, Solar Electric Propulsion (SEP) is of particular interest because it offers higher specific impulse compared to the chemical propulsion and consequently higher propellant efficiency [26]. For this reason, despite not producing enough thrust to leave the Earth's atmosphere, it represents an ideal propulsion technology once on-orbit, especially for unmanned missions where travel time is less critical.

Several high-power SEP concepts are being developed to show how electric thrusters could be used for near-Earth applications and scaled up for ambitious deep space missions, providing significant fuel saving in comparison with conventional chemical propulsion. Among these concepts, the lower power ones represent missions that could be currently implemented to gain experience with these kinds of vehicles, whereas the higher power concepts help to envision how the technologies could scale to enable future capabilities.

## 1.2 Near-Earth Transportation Mission Concepts

In near-Earth missions electric propulsion could be conveniently implemented on servicing vehicles, envisioned to provide various services on-orbit, like orbital payload transfer, end-of-life satellites disposal and space debris removal, on-orbit assembly and life extension refueling. The electric thruster power required in these kinds of missions could approximately span a power range of tens of $kW$.

EPS could be implemented in a reusable and versatile electric space tug for Earth satellites servicing. An electric space tug could be exploited in support of satellites transfer maneuvers from Low Earth Orbit (LEO) to higher operational orbit. In this scenario the pre-deployed tug is supposed to actively perform rendezvous and docking with the satellite, which has been released by the launcher in a non-definitive low orbit, and to bring and release it to the expected operational orbit [8]. Thus, the satellite would not need to perform the final transfer to its operational orbit: this allows reducing the propulsion on the satellite, in favor of a greater payload mass capability.

A similar system could be used for removal of space debris from near-Earth orbits. Nowadays, there is a growing interest to provide active debris removal to reduce the potentially dangerous objects, such as inactive satellites and launcher upper stages, accumulated over 50 years of space activities [7]. The new international standards, shared by the main space agencies, put a limit on the accumulation of masses in space. They require either the de-orbiting of an inactive satellite in no more than 25 years (if the satellite is in LEO) or a disposal maneuver for the re-entry or the positioning in a graveyard orbit (for satellites in geostationary orbits or in medium Earth orbits).

If coupled with a reusable re-entry vehicle, the electric space tug system could support the retrieval of significant payload samples on Earth: in this case the two systems would rendezvous in a defined orbit in order to move the payload sample from the space tug to the re-entry vehicle and return it back to Earth [8].

## 1.3 Cislunar Transportation Mission Concepts

The cislunar environment represents the proving ground to test and demonstrate the systems on which long-duration missions into deep space shall rely. In fact, cislunar environment provide conditions similar to that encountered in deep space. Significant work is required to mature technologies before embarking on missions that are independent of Earth. The cislunar flight testing is therefore a necessary step to enable the use of high power SEP for deep space transportation missions.

According with the NASA's approach to the exploration beyond LEO, the focus of lunar vicinity phase is the assembly of the Lunar Orbital Platform-Gateway (LOP-G), a planned lunar-orbit space station, whose power and propulsion capabilities would be provided by the Power and Propulsion Element (PPE), a $40kW$ SEP system augmented with a chemical reaction control system.

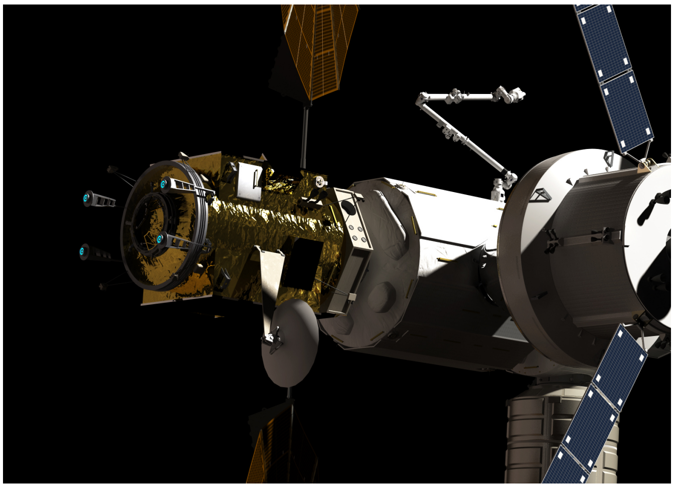


Figure 1.1: A model of the PPE (left) at the LOP-G

The PPE would be in charge of maneuvering and transferring the LOP-G between various orbits to support different types of missions [3]. It is expected to be around an order of magnitude more powerful than the propulsion system used on missions like Dawn and, since Mars transportation systems may need to be another order of magnitude more powerful, it represents a good intermediate testing platform. The PPE is conceived to incorporate a lot of the technologies NASA was developing for the Asteroid Redirect Mission (ARM), now cancelled.

ARM concept was that of using SEP to redirect a large amount of asteroidal mass to a lunar orbit where crew could have collected and analyzed samples without requiring long-duration human transport [18, 19]. The asteroidal mass could have been an entire asteroid or a boulder extracted and a $40kW$ SEP system was envisioned to accomplish the objective. Beyond testing an advanced SEP system and demonstrating planetary defense technique, ARM goal was that of providing a high-value target in cislunar space, that would have required a human presence to take full advantage of this new resource.

Moreover, the presence of a lunar outpost poses the issue of its maintenance and sustainment: for these purposes, an electric space tug could be involved, especially when unmanned and logistics transportation missions are considered

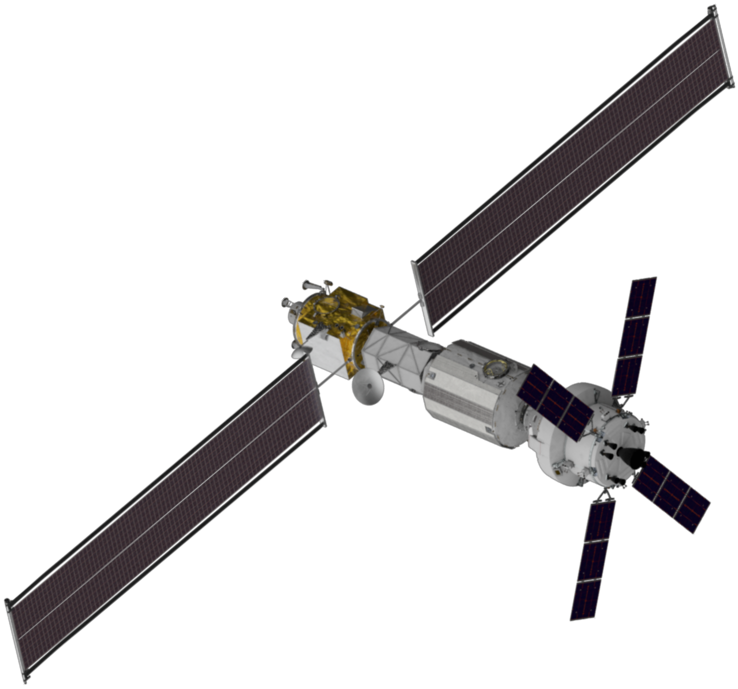


Figure 1.2: A LOP-G conceptual construction; PPE is shown on the left side

[13, 14, 17]. In this scenario the transfer time is less critical then in ones in which the human factor is involved. This kind of missions includes the delivery of logistics and supplies to maintain and resupply the station as well as the transfer of infrastructures for its growth and development.

## 1.4 Deep Space Transportation Mission Concepts

The cislunar space represents the next step in the human space exploration pathway, but the progressive expansion of human capabilities calls for Mars and other deep space destinations. Experience and knowledge gained while operating in the lunar vicinity would be necessary when facing with challenging missions to farther targets.

NASA's Evolvable Mars Campaign investigates a split architecture that employs SEP to pre-place cargo to Mars and chemical propulsion to transfer the crew: while the high efficiency of a SEP system is ideal for delivering cargo to Mars, long trip times associated with low-thrust trajectories are undesirable for crew health and safety. This split architecture draws on the strengths of each technology to perform two complementary functions required for Mars human exploration. In this concept a SEP system, providing $150kW$ of electric thruster power, will be necessary to deliver on a Mars orbit elements such as habitats, orbital maneuvering systems, consumables, and landers for use in the Mars environment, including Phobos and Deimos environments [19].

Lockheed Martin's Mars Base Camp concept also involves SEP to pre-deploy assets in Mars orbit and haul items to cislunar space, where they would be assembled and tested before going to Mars. In particular in this concept the $200kW$ class SEP would be in charge of pre-place the Phobos/Deimos excursion system, the laboratory and science equipment, the center node and certain consumables that are not required for survival [5, 6]. Also in this case less time critical cargo delivery is, therefore, entrusted to electric propulsion.

Before preparing human missions in vicinity of Mars, however, an important milestone would be a robotic Mars sample return mission, which could represent a good candidate to exploit SEP. High scientific value would derive from the analysis of the sample, nevertheless, many new technologies would be required to carry out this pioneering mission: a landing system, an ascent vehicle, a rendezvous system in Mars orbit and an Earth re-entry vehicle.

Other ambitious objectives are Near-Earth Asteroids (NEAs). In this frame a NASA's study investigated the use of SEP to transport crew directly to a NEA [19]. In fact, small body rendezvous missions such as NEAs missions are expected to receive significant benefits in term of cost savings when SEP is used. It is no coincidence that missions Deep Space 1, Hayabusa and Dawn, all of them using SEP, have visited small bodies. A NASA's SEP concept for human exploration of NEAs consists of a mission in which a SEP stage together with a space habitat and an excursion vehicle rendezvous with the Multi-Purpose Crew Vehicle and a chemical stage. After the Earth-departure burn provided by the chemical stage, the rest of the heliocentric transfer to and the rendezvous with the NEA is performed by the SEP stage, as well as the return trip of the crew vehicle to Earth orbit.

In the region of the Inner Solar system Venus and Mercury have always been of extreme interest and our knowledge of them is far from being completed. Currently BepiColombo, an exploration mission to Mercury, has been planned, carried out jointly by the European Space Agency (ESA) and the Japan Aerospace Exploration

Agency (JAXA) [2]. Two spacecrafts will be launched together and in a stacked configuration with the propulsion element, the Mercury Transfer Module (MTM). From their operative orbits two spacecrafts, the Mercury Planetary Orbiter (MPO) and the Mercury Magnetosphere Orbiter (MMO) will study the planet and its environment. The major part of the $\Delta V$ required during cruise is provided by the SEP system of the MTM, while a bi-propellant propulsion system is used for attitude control.

Scientific/robotic missions towards outer planets of the Solar System are the long-term exploration opportunities that would be opened by next SEP generations. The long-duration, high-efficiency operations of SEP systems enable mission that can be difficult and expensive to design implementing a propulsion system based on chemical propulsion. Possible targets identified are the moons of Jupiter and Saturn, Uranus and Neptune to search for evidence of life.

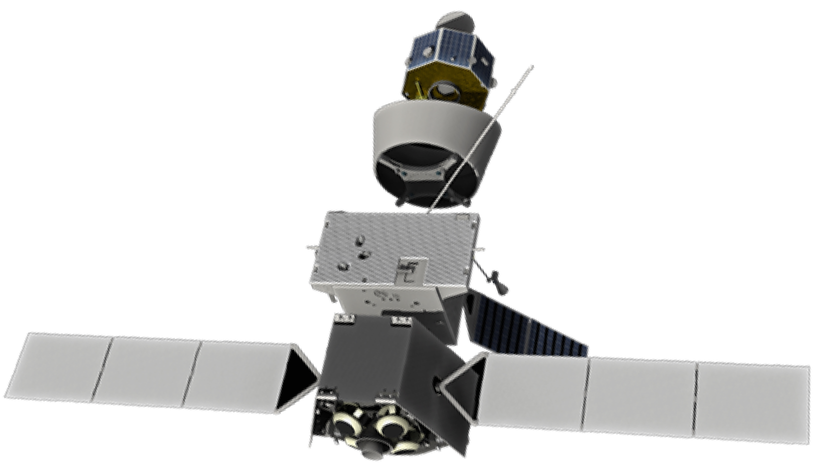


Figure 1.3: BepiColombo elements; from the bottom up: the MTM, the MPO and the MMO

## 1.5 The Moon-Mars Transportation Mission Concept

The analysis of transportation mission scenarios, exploiting high power electric propulsion, between Moon and Mars is the scope of this study. The root problem is the realization of cargo transfer between the LOP-G referred to in paragraph 1.3 and an orbital station around Mars. The mission aims to link these two architectures to support cis-Martian space exploration through the delivery, from the lunar environment, of assets and supplies necessary to sustain the Mars-orbiting outpost and its operations. A general overview is given for both station concepts.

### 1.5.1 The LOP-G Concept

NASA has planned to place the habitable spacecraft LOP-G at the Near-Rectilinear Halo Orbit (NRHO). As referred to in paragraph 1.3, LOP-G will include the Power and Propulsion Element (PPE), the advanced SEP service module developed thank to a public-private partnership, that will provide both orbital maintenance and transfer between lunar orbits. Other fundamental elements will be a habitation element, a logistic element and an airlock, which, together with the visiting Orion spacecraft, will constitute the habitable elements of the station. These main elements will enable a crew of four members to live and work in cislunar space for at least 30 days.

Feasibility trades and future works will determine which additional elements will extend the platform capabilities. They could be partner-provided elements to support science and technology activities, as well as lunar landers to enable missions to the lunar surface. They could include also elements for the assembly of the Deep Space Transport (DST), a crewed interplanetary spacecraft concept to support science exploration missions to Mars of up to 1000 days. The DST is envisioned to depart from the LOP-G and return there, in order to be refueled and reused.

Scientific operations and opportunities at the LOP-G and other possible activities will aim to demonstrate many capabilities that will be needed for deep space mission including telerobotics and sample return. LOP-G could also have an important role in staging human missions to the lunar surface. In this case LOP-G additional functions will be required, such as providing storage and refueling of a reusable ascent module and providing safe haven for crew aborting from the surface.

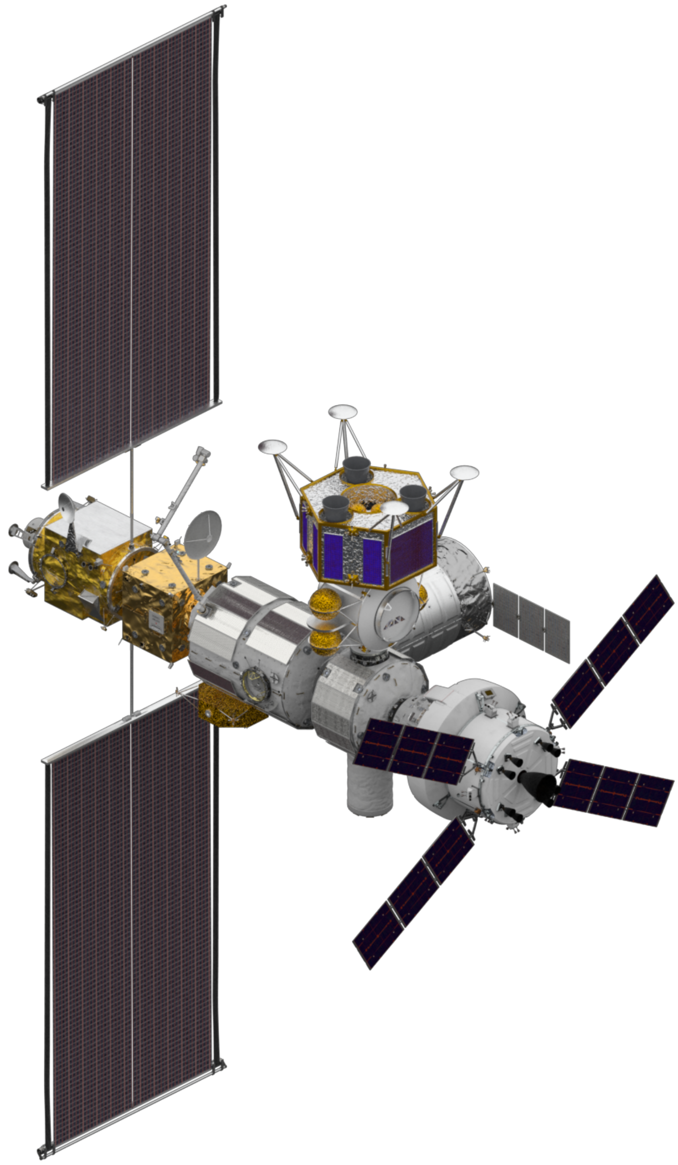


Figure 1.4: A LOP-G conceptual construction with the added lander to enable lunar surface mission scenarios

### 1.5.2 The Mars Orbital Station Concept

Many mission concepts for expeditions to Mars were proposed in the late decades and in most cases an orbiting station around Mars is the core element. This allows close observation of the Red Planet and provide a platform for exploration of the Mars environment and surface. In the analysis proposed in this study the orbital outpost at Mars is referred to as "Mars Orbital Station" and abbreviated as "MOS". Its characteristics are assumed to be the most widespread among that of some remarkable proposal until now envisioned in the frame of manned missions to Mars. A comparison between different concept is shown in Table 1.1, which contains the overall mission highlights for every concept. Subject of this comparison are:

- The Human Exploration of Mars Design Reference Architecture 5.0 (DRA 5.0), released by NASA in 2009 [10];
- Project $M^3$, a study for a manned Mars mission in 2031, developed during the Space Summer School in Alpbach in 2003 [24];
- Mars Base Camp, an architecture for sending human to Mars presented in 2016 by the American company Lockheed Martin [5, 6];
- The Interplanetary Expedition Complex (MEK), a Russian concept for an orbital human mission to Mars developed and designed by the Russian manufacturer RKK Energia [9];

In $M^3$, MBC and MEK concepts, an orbital station around Mars is conceived as a close-up outpost from which short-duration surface missions, involving only part of the crew, can be carried out through the exploitation of ascent-descent vehicles. In DRA 5.0, instead, the mission is a long-duration surface mission involving all the crew. Once arrived in Mars orbit aboard the Mars transfer vehicle (MTV), the crew perform a rendezvous with the surface habitat, previously deployed, which would serve as the transportation vehicle to the surface, while the MTV remains in orbit, waiting for the crew return. In the table MTV features are considered for the DRA 5.0 column.

In view of these considerations, we assume the Mars Orbital Station as an orbital station in a 1-sol orbit around Mars with a crew of six confined in 500 $m^3$ of pressurized volume. It is conceived for a total mission of three years, exploiting Nuclear Thermal Rocket (NTR) propulsion for in-space transfer and solar arrays for electric power generation. For its assembly, each module which composes the multi-modular station will be launched in a High Earth Orbit. The final total mass of the station will be between 500 and 700 tons including the ascent-descent module envisioned for short-duration surface missions involving only part of the crew.

In the following chapters, the Mission Analysis performed by a high-power electric space tug in a cargo transfer scenario between the LOP-G and a generic Mars habitat, referred to as Mars Orbital Station (MOS), is described

| | DRA 5.0 | $M^3$ | MBC | MEK |
|---|---|---|---|---|
| **Mission Length (yrs)** | ~6 | ~3 | ~3 | ~2 |
| **Mars Orbit (km)** | 1-sol (250 x 33,793) | ~350 | 1-sol (250 x 33,793) | 1-sol (250 x 33,793) |
| **Martian Orbit Stay (months)** | - | ~18 | ~11 | ~1 |
| **Surface Stay (months)** | ~18 | ~0.5 | ~0.5 | ~0.5 |
| **Propulsion Type** | Nuclear Thermal Rocket (NTR) | Bimodal Nuclear Thermal | Cryogenic | Solar Electric |
| **Power Generation** | Solar Electric | Bimodal Nuclear Thermal | Solar Electric | Solar Electric |
| **$I_{sp}$ (s)** | 900 | 1000 | 440 | 3970 (Ion Thrusters) |
| **Crew Size** | 6 | 6 | 6 | 6 |
| **Mass to LEO (t)** | ~356 (MTV) | ~756 | ~726 | ~510 |
| **Pressurized Volume ($m^3$)** | ~342 (MTV) | ~825 | ~720 | ~410 |
| **ISRU** | yes | no | no | no |

Table 1.1: Data comparison for the different Mars mission concepts

In Chapter 2, an overview of the analysis methodology adopted is presented and the tools used for system definition and mission definition are specified. The Mission Statement and the Primary and Secondary Objectives are presented and described in Chapter 3. Chapter 4 goes deeper in the system definition at both system and subsystem level. In Chapter 5 different mission scenarios are identified and mission analysis is presented for two of them. In Chapter 6 a trade-off analysis is carried out to identify which is the best scenario between those considered.

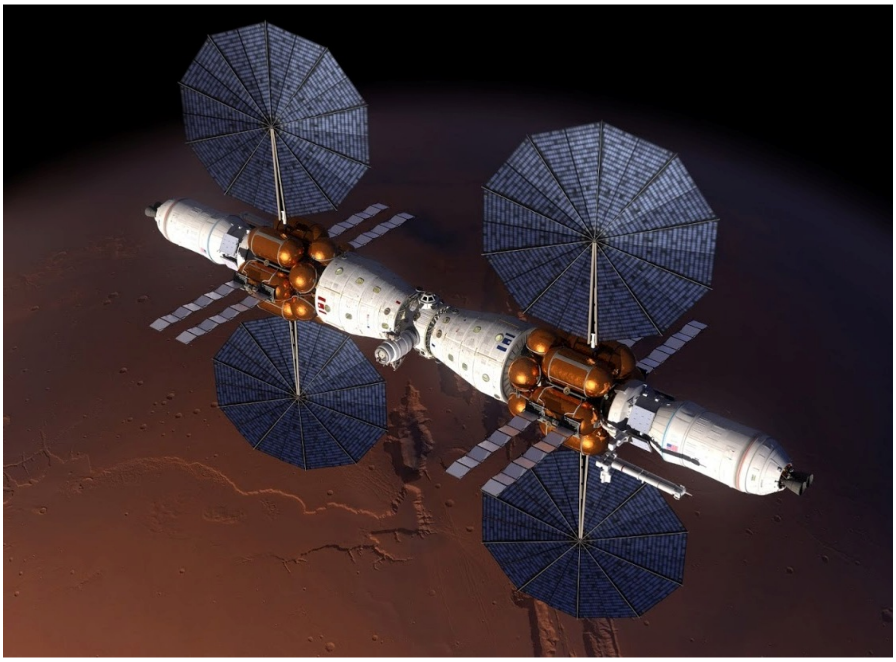


Figure 1.5: Mars Base Camp configuration in Mars orbit


Figure 1.6: MTV "In-Line Configuration" in LEO prior to departure

# Chapter 2

# System and Mission Analysis Methodology

## 2.1 Analysis Process

The approach to complex problems, from the system engineering point of view, follows an iterative and recursive procedure, in which the application of processes is repeated to define ever lower layer of the system composition, allowing to go deeper in detail in the analysis of its configuration [25]. Typically steps of this process are schematically illustrated in 2.1. These steps allow a continue refinement of requirements, leading to a more thorough system definition.

The very first step is the definition of the Mission Statement, a clear and concise declaration of mission purpose for existence, which is at the basis of the mission concept. It shall qualitatively identify the goals of the mission and the drawback results obtained from it.

Once the Mission Statement has been drawn, the mission objectives and constraints are derived. They drive the analysis and the design of the whole mission. The Primary Mission Objectives, specifically, can be directly derived from the Mission Statement, while additional objectives, called Secondary Mission Objectives, can be determine through the Stakeholders Analysis. This analysis is usually subdivided in two consecutive steps: firstly, it is necessary to identify all the stakeholders, i.e. all the main actors involved in the mission, secondly, it is necessary to determine their needs and expectations. Mission Constraints are other crucial issues that impose some limitations to the mission analysis and design.

The Mission Statement, Objectives and Constraints shall be fixed early because they represent the mission foundation. For this reason they cannot be modified or re-adapted during the following iterations. After their setting, the essence of the analysis process can be split in two main branches: the Functional Analysis and the Concept of Operations, which aim at a better characterization of the systems involved in the mission, and the mission operations, respectively.

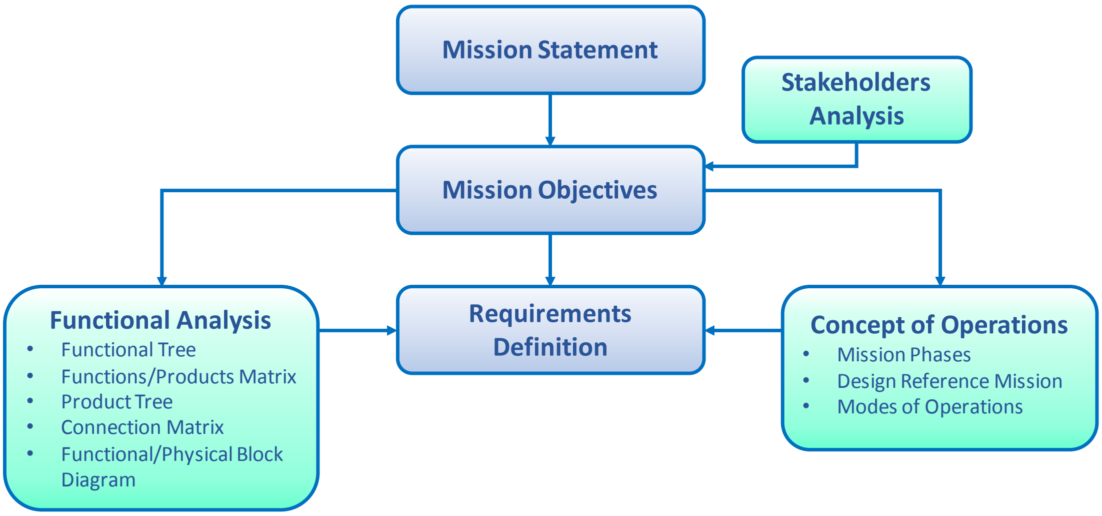



Figure 2.1: General methodology overview

## 2.2 Functional Analysis

Functional Analysis is a fundamental tool of the analysis process to investigate a new concept and determine its architecture from the functional point of view. The Functional Analysis is a recursive process, meaning that it shall be repeated starting from the highest level (System of Systems) to the successive lower layers (System, Subsystem, Equipment, etc.). Once applied to the various levels, it allows defining the functional architectures of the System of Systems, the System and the Subsystem layers.

For sake of clarity, we can think that the functional System of Systems architecture is completed when all its elements, i.e. the Systems, have been identified and their relations determined. Analogously, the elements of the System architecture are the Subsystems while in the Subsystems architecture they are the Equipment. This product breakdown is useful to gradually refine the requirements that shall have to be satisfied to fulfill the mission.

The steps to be accomplished in order to carry out the Functional Analysis are:

- Functional Tree;
- Functions/Products Matrix;
- Product Tree;
- Connection Matrix;
- Functional/Physical Block Diagram;

Figure 2.2 shows the flow-chart of the proposed Functional Analysis, illustrating all its steps ad their sequence.

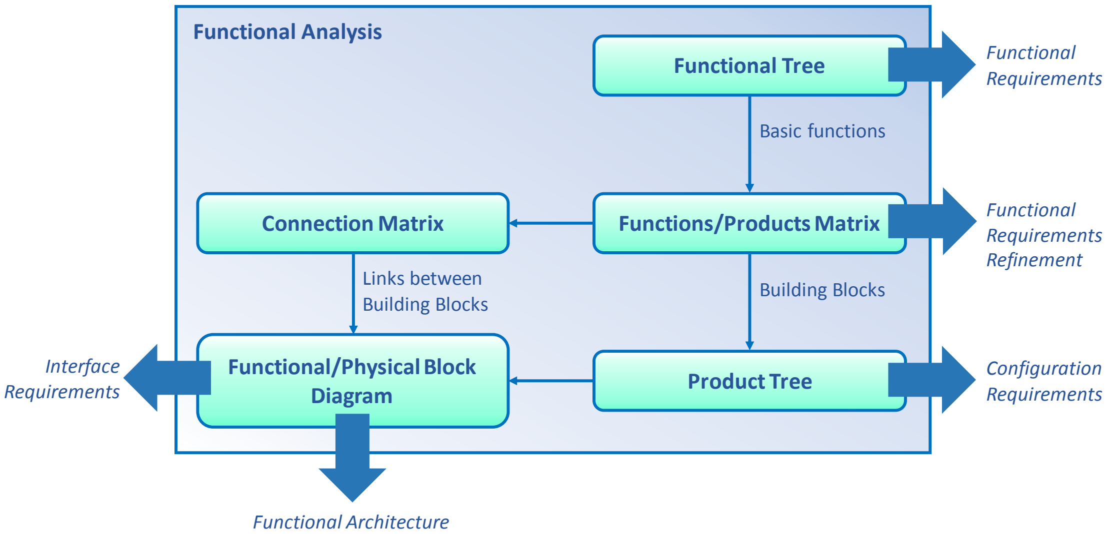



Figure 2.2: Functional Analysis flow-chart

A primary result of the Functional Analysis is the **Functional Tree**, which allows splitting the higher level functions, deriving from mission objectives and constraints, into lower level ones. The aim is to identify the basic functions that have to be performed. Higher level functions represent complex tasks that need to be decomposed into ever simpler ones, until basic functions are detected. These are at the bottom of the tree and cannot be split any further. The lower level functions can be obtained from the higher level ones by asking "how" that higher level function can be performed. Conversely, from higher level we can move to lower level by asking "why" that function has to be performed. Figure 2.3 clarifies this process.

For the System of Systems level, the basic functions are those corresponding to Systems task, they stay at the bottom of the System of Systems Functional Tree, but are at the top of the Functional Tree at System level. Similarly, for the System level, the basic functions are those corresponding to Subsystems tasks and which stay at the top of the Functional Tree at Subsystem level. Eventually, for the Subsystem level, basic functions are related to Equipment functions.

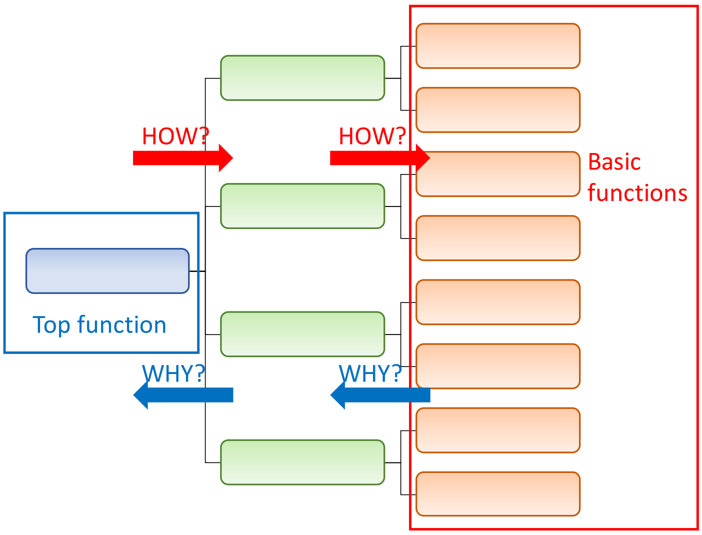



Figure 2.3: Functional Tree

After identifying the basic functions for the level considered, we need to choose the elements that will perform those functions. This is obtained by means of the **Functions/Products Matrix**, which allows us to match the basic functions to the relative elements able to perform them. Basic functions are written in the rows of the matrix while products will be in the columns. Simply asking ourselves which element is able to perform the function under consideration, we can add a new column containing the corresponding element, if not yet identified, and tick their intersection. Eventually all necessary products are determined. They represent the so-called “Building Blocks”, i.e. the elements constituting the functional architecture for the level under consideration.

As third step, the Product Tree is generated by grouping the Building Blocks. Figure 2.4 gives evidence of these processes. Depending on whether the level considered is Subsystem, System or System of Systems, the Building Blocks will be respectively Equipment, Subsystems or Systems. When the Building Blocks are Systems, for example, they may be grouped into segments to form the Product Tree of the System of Systems.

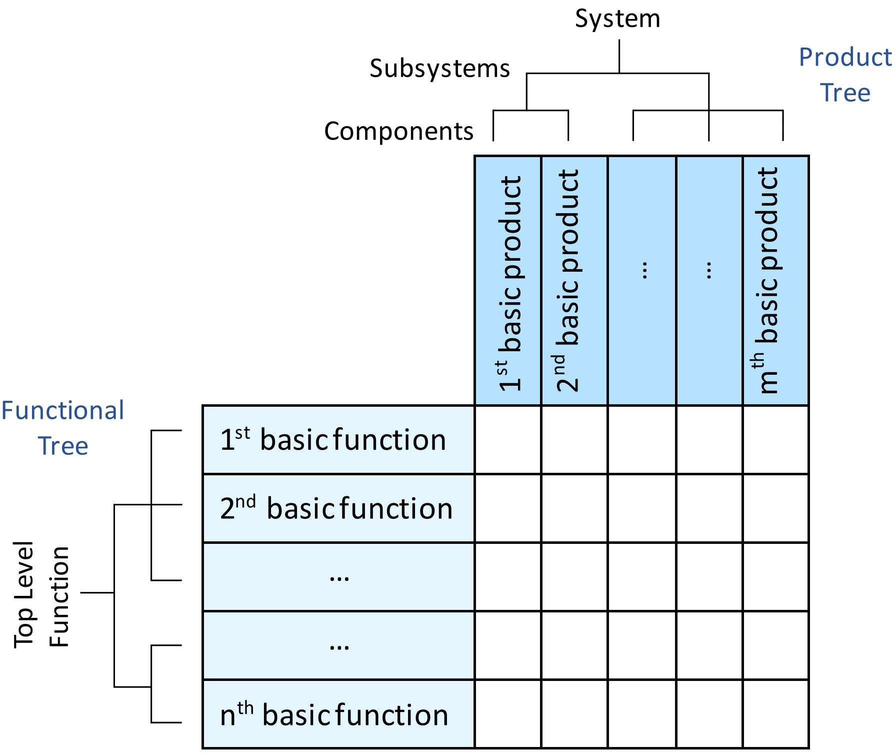



Figure 2.4: Functions/Products Matrix in relation to Product Tree and Functional Tree

Once the Building Blocks have been identified, the next step is to make evidence of their interconnections by means of the **Connection Matrix**. In this matrix both rows and columns contain the Building Blocks and the intersection between two elements is ticked when a connection between them is identified. Information about the nature and the directionality of the connections are not yet given. To provide them, a further step is necessary: the **Functional/Physical Block Diagram**, in which the Building Blocks are linked through arrows that highlights where the connections are pointing to, and what kind of links they are, if electrical, mechanical or data link, etc. Both steps are schematically represented in Figure 2.5.

After developing the Connection Matrix and the Functional/Physical Block Diagram, the functional architecture for the level concerned is broadly determined and the relationships between the various components clearly identified.

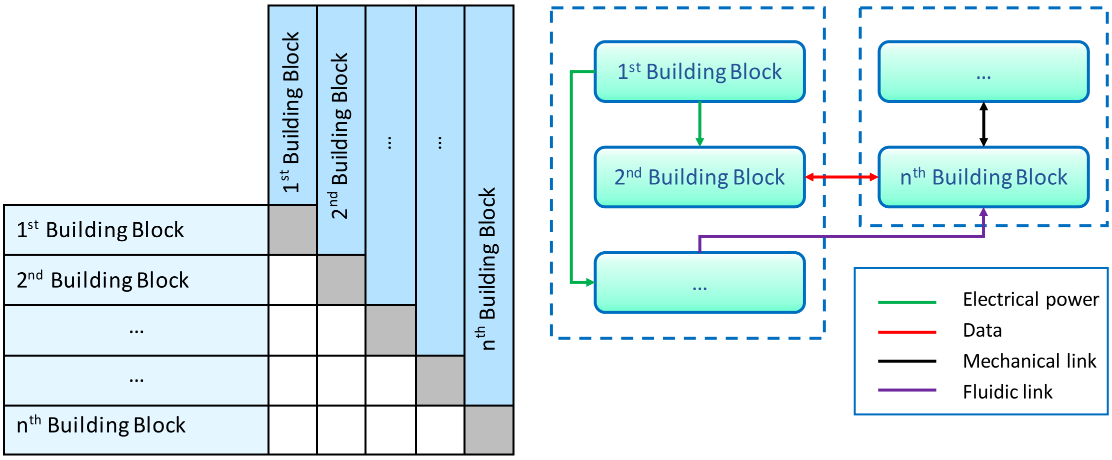



Figure 2.5: Connection Matrix and Functional/Physical Block Diagram

## 2.3 Concept of Operations

The Concept of Operations (ConOps) is a description of how the system will be operated during the mission in order to meet stakeholders' expectations. It is an important step in mission analysis because it provides an operational perspective, allowing the derivation of requirements more specifically related to the use of the system. The operational point of view of the system, assessed through the ConOps analysis, often allows the designers to reveal system functions that have not been considered before. Furthermore, ConOps serves as the basis for specific operational documents that should be defined later during the mission planning.

The definition of the ConOps is also an iterative process that has to be performed until the desired level of detail. The ConOps can include many aspects of operations, such as: Mission Phases, Modes of Operation, Mission Timelines, Design Reference Missions (DRMs) and/or Operational Scenarios, End-to-end Communication Strategy and/or Command and Data Architecture, Operational Facilities, Integrated Logistic Support (i.e. resupply, maintenance and assembly information) and Critical Events. Among these tools, the ones chosen for the ConOps development in the present study are:

- Mission Phases
- DRMs
- Modes of Operations

In the **Mission Phases** the major phases of the mission are time-sequentially described. To properly delineate the phases, it's important to consider the various external environments, both natural and induced, in which the system has to operate, in terms of loads, temperatures, pressure, radiation and other critical environmental factors. Each environment defines the general state of the system operating in those specific conditions and, therefore, characterizes a different mission phase. This characterization has to be done for the full system life-cycle, from the deployment to the disposal.

The **DRM** provides a visual representation of the mission phases and their sequence. It shows the Building Blocks involved in the various phases and in which orbits they are. Figure 2.6 provides an example of a DRM from our study, this would be fully explained in Chapter 5.

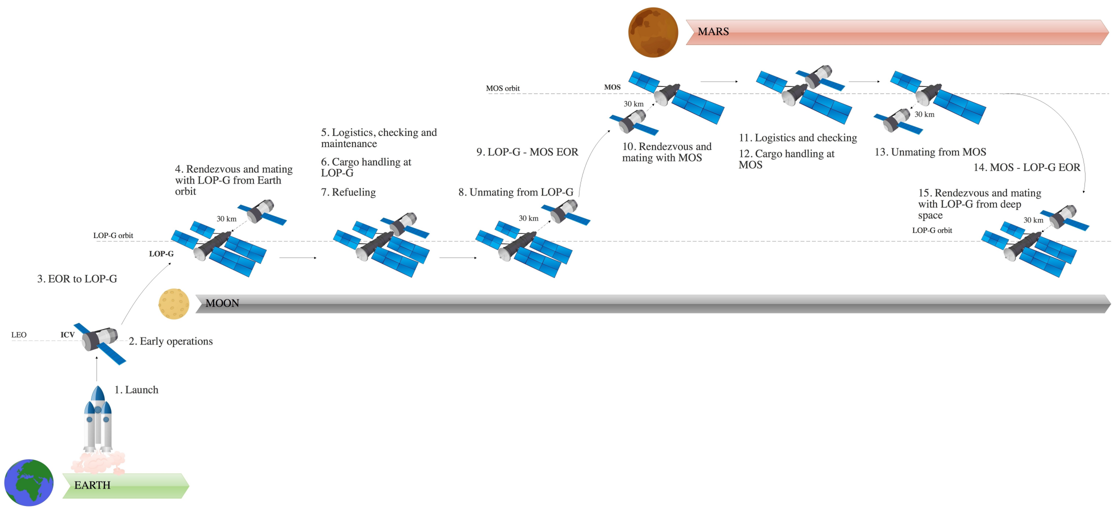
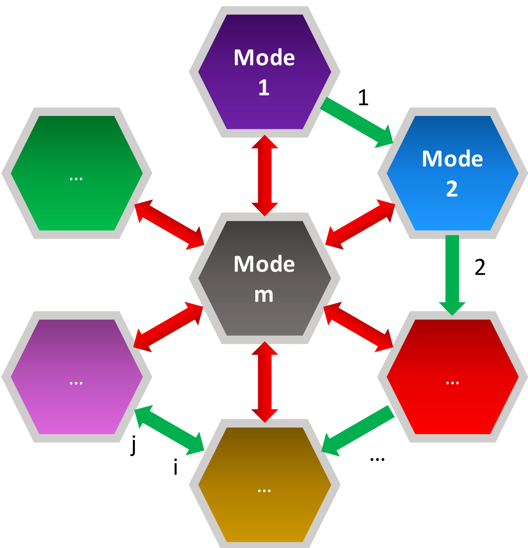



Figure 2.6: An example of Design Reference Mission

During each mission phase, the system can enter in various **Modes of Operations**. A Mode of Operation is an operational state of the system determined by a precise definition of all subsystems and equipment that have to be activated or not in that specific mode. Table 2.1 is useful to describe all the possible modes that can be triggered by the system during the various mission phases. When the mode is accessible in a particular phase, their intersection is ticked. In addition to characterizing the Modes of Operations, it is also important to highlight which transitions between the different modes are possible and in which cases these transitions occur. Diagrams and tables like those shown in Figure 2.7 provide this kind of information, clarifying all possible transition events.

| Phases \ Modes | Mode 1 | Mode 2 | … | … | Mode m |
|---|---|---|---|---|---|
| Phase 1 | X | | | | |
| Phase 2 | | X | | | X |
| … | X | | | | |
| … | | | X | | |
| Phase n | X | | | X | |

Table 2.1: Mission Phases/Modes of Operations table




| | From | To | Transition event(s) |
|---|---|---|---|
| 1 | Mode 1 | Mode 2 | |
| 2 | Mode 2 | … | |
| … | … | … | |
| i | … | … | |
| j | … | … | |
| … | All | Mode m | |
| … | Mode m | All | |

Figure 2.7: Modes of Operations transition diagram and table

## 2.4 Requirements Definition

We said in previous paragraphs that all the steps considered in the analysis process are important drivers for the requirements definition. But why are requirements so important and what they allow us to obtain? Requirements are brief and concise recommendations, describing which are the characteristics and the capabilities that the system should satisfy. In the requirements definition process the stakeholders' expectations are transformed into a complete set of validated requirements expressed as "shall" statements, that must be unambiguous and verifiable. Keeping track of all derived requirements is extremely helpful, especially when submitting the design to the review phases, in order to understand if it is compliant to stakeholders' expectations.

Through the proposed methodology different categories of requirements can be generated. The relations between these categories and the main tools of the methodology used to derive them are illustrated in Figure 2.8. They include:

- *Mission Requirements*: requirements related to a task, a function, a constraint, or an action induced by the mission scenario. They directly derive from Mission Statement and Mission Objectives and Constraints.
- *Programmatic Requirements*: other top-level requirements deriving from objectives and constraints imposed by the stakeholders, more related to schedule, cost and strategies.
- *Functional Requirements*: requirements that define what the product shall perform, in order to conform to the needs/Mission Statement or requirements of the users. They derive from the basic functions of the Functional Tree and are successively refined through the Functions/Products Matrix information.
- *Configuration Requirements*: requirements dealing with the product composition and its organization. They are deduced from both the Functions/ Products Matrix and the Product Tree.
- *Interface Requirements*: requirements which specify the connections existing between the Building Blocks. They can be determined through the Connection Matrix and are subsequently refined with link type information through the Functional/Physical Block Diagram.
- *Environmental Requirements*: requirements related to the system environment during its life cycle; this includes the natural environments and induced environments. They can be derived from the Mission Phases analysis.
- *Operational Requirements*: requirements dealing with the system operability. They can be determined from the Modes of Operations analysis.

From the requirements listed above, additional categories of requirements can be derived. In this study will be provided some examples of *Performance Requirements*, which can be established from Functional Requirements. They describe quantitative features related to the functions expressed in the Functional Requirements.

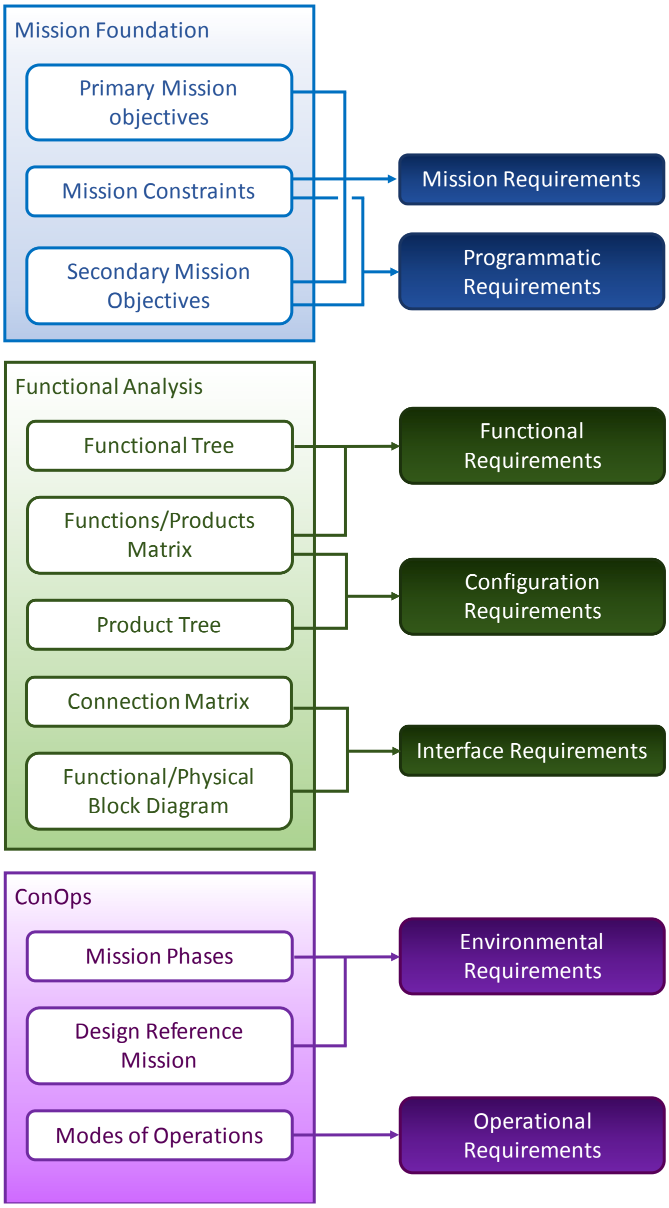



Figure 2.8: Requirements Definition Process

# Chapter 3

# Mission Objectives and Functional Analysis at System of Systems Level

## 3.1 Mission Basis

### 3.1.1 Mission Statement and Constraints

A set of questions can be used to properly drawn up the Mission Statement which represents the mission purpose, what the mission needs to achieve and why.

*What is the root problem?*

The root problem is the realization of cargo transfer between cislunar and Mars proximities. We aim to link these two environments to support cis-Martian space exploration through the delivery of supply, fuel, habitat modules, and other material necessary to sustain the Mars-orbiting outpost and to make it growth. A robust logistic strategy is therefore necessary to deliver assets provided via the Moon.

*How can the issue be solved?*

The issue can be solved by designing a system adopting high power electric propulsion, that shall provide cargo transfer between the two stations.

*Are there other significant constrains imposed by top level scenario?*

The system should be able to accomplish multiple end-to-end transfers: it is conceived as a reusable system and it should exploit existing infrastructures at LOP-G and MOS. Furthermore, to extent its serviceability to many scenarios as possible, the system shall be able to support the MOS in different phases of its operational lifetime.

In view of these considerations both the Mission Statement and Mission Constraints can be set down.

**MISSION STATEMENT**

*In order to support cis-Martian space exploration, the mission will provide cargo transportation between the Lunar Orbital Platform-Gateway and the Mars Orbital Station, through an electric-propelled system able to transfer every resource necessary to sustain the Mars station infrastructure in its initial development, successive evolution, as well as in its operations and crew support.*

**Mission Constraints**:

- The transportation system shall transfer end-to-end unmanned payloads exploiting existing infrastructures;
- The transportation system shall be conceived as a reusable space transportation system able to perform multiple transfers and on-orbit refueling operations;
- The transportation system shall provide support to the Mars Mission[1] during all phases of its extended mission timeframe.

Since space operations over the long term need to be sustainable to advance human exploration capabilities, the system is conceived as reusable. For the purposes of this study, reusability is the ability to use a system for multiple missions without the need for replacement of systems or subsystems. Only replenishment of consumable commodities, such as propellants, occurs between missions. Dedicated refueling operations shall, therefore, be envisaged.

### 3.1.2 Mission Objectives

As explained in paragraph 2.1 Primary Mission Objectives should come largely from the Mission Statement and represent the broad goals of the mission.

[1] "Mars Mission" indicates the mission of exploring cis-Martian space by means of the MOS, this is the broader mission within the mission of the transportation system is intended to provide service.

**Primary Mission Objectives**:

- To support cis-Martian space exploration;
- To provide transportation system between LOP-G and MOS;
- To sustain development, evolution, operations and crew support of the Mars Orbital Station;
- To employ electric propulsion.

To properly derive Secondary Mission Objectives, it's necessary to carry through with the **Stakeholders Analysis**. Therefore, stakeholders shall first be identified and then their expectations shall be determined. Since the mission under consideration is not foreseen within the actual space context, we just provide a general overview of reasonable stakeholders for the main stakeholders' categories. These are:

- **Sponsors**, associations or private who set down mission statement, establish bounds on schedule and funds availability. Considering our mission they may be *National Space Agencies* of the current ISS and the future LOP-G participating countries and their Commercial Partners.
- **Operators**, people in charge of controlling and maintaining space and ground assets. They typically consist of engineering organization. In view of our mission, they may be *Private Space Companies*, which develop main technological features, *Private Suppliers*, which provide services and resources for certain portions of the system operations and *National Space Agencies*, which provide existing facilities.
- **End-users**, people that receive and use the space mission's products and capabilities. Considering that our mission is in support of the broader Mars Mission, in this case end-users may include the *National Space Agencies* of the current ISS and the future LOP-G participating countries and the *Scientific Community*, which would take advantage of the huge science return from exploring cis-Martian space.
- **Customers**, users who pay fees to use a specific mission's product. Reasonably, the may not be expected in the primary context of our mission, but we can think that, in a possible platform evolution, there might be interest from *Private Space Companies*in paying a fee to use the cargo vehicle for materials transportation.

Stakeholders' expectations and needs constitute the Secondary Mission Objectives. To fix them, we have considered which could be the crucial issues for the realization of our mission, that the stakeholders would need to stress.

**Secondary Mission Objectives**

- To standardize mating elements and interfaces for rendezvous and docking;
- To exploit existing ground and launch facilities necessary to support launch and orbital insertion;
- To exploit existing space facilities for on-orbit refueling;
- To deliver assets in compliance with schedule and needs identified in the various scenarios;
- To allow highly autonomous unmanned in-space operations;

From the Mission Statement and Mission Objectives and Constraints, *Mission Requirements* and *Programmatic Requirements* have been derived. They are listed in Appendix A.

As the mission has been identified, we assign it a name and a logo. Thus, in following chapters the considered system is referred to as "Interplanetary Cargo Vehicle" or "ICV" and its mission is "The ICV mission".


Figure 3.1: Mission logo

## 3.2 Functional Analysis at System of Systems Level

### 3.2.1 Segments Identification

To provide the starting point for the Functional Tree we need to identify a top level function deriving from the Mission Objective and Constraints that could represent the primary, broad, complex function for the mission to be performed. We have expressed it as: *To perform multiple end-to-end cargo transfers between lunar and mars proximities.* This can be split in four main high level functions, as indicated in Figure 3.2 :

1. To provide launch capabilities;
2. To provide transportation capabilities;
3. To provide mission support capabilities from orbit;
4. To provide mission support capabilities from Earth.

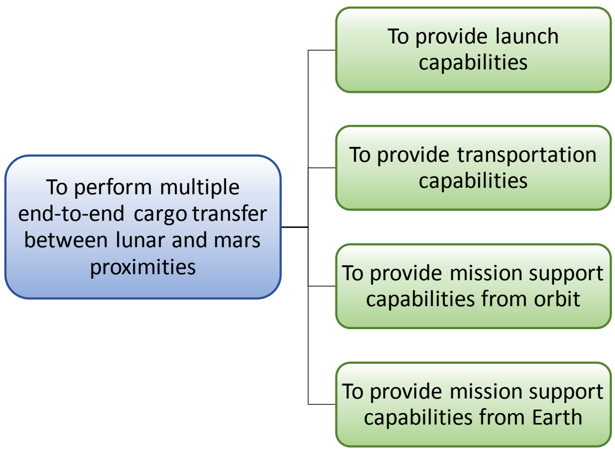



Figure 3.2: Top Level Functional Tree

From these four main functions early functional requirements can be generated. They are "shall" statement expressing the tasks indicated in the functions.

*Functional Requirements*

- Launch capabilities shall be provided;
- Transportation capabilities shall be provided;

- Mission support from orbit shall be provided;
- Mission support from Earth shall be provided.

The four main functions are to be ascribed to the Mission Segments through the Functions/Products Matrix illustrated in Figure 3.3 on the left side. The Launch

| | | SoS Segments | | |
|---|---|---|---|---|
| | | Launch Segment | Space Segment | Ground Segment |
| Functions | To provide launch capabilities | X | | |
| | To provide transportation capabilities | | X | |
| | To provide mission support capabilities from orbit | | X | |
| | To provide mission support capabilities from Earth | | | X |

| | Launch Segment | Space Segment | Ground Segment |
|---|---|---|---|
| Launch Segment | | | |
| Space Segment | X | | |
| Ground Segment | X | X | |

Figure 3.3: Functions/Products Matrix (left) and Connection Matrix (right) - Segments Level

Segment include systems and facilities necessary to perform launch, the Space Segments is related to on-orbit mission elements, while the Ground Segment consists of all the ground-based control facilities. Understandably, they are all interconnected, as shown in the Connection Matrix on the right side of Figure 3.3 .

### 3.2.2 Systems Identification

To define the elements being part of the functional architecture at System of Systems Level, it is necessary to extent the Functional Tree until it is possible to identify functions related to specific systems. The basic functions for the System of Systems Level are shown in Figure 3.4 at the bottom of the Functional Tree.

Since reusability is included in mission objectives, specific functions related to refueling operations have to be taken into account when splitting the *To provide mission support capabilities from orbit* function into lower-level functions. It should also be considered that, in a more crowded space, space assets providing coordinates necessary to enhance autonomous navigation are to foreseen. Navigation capabilities should, therefore, be provided both in cislunar proximity and in mars proximity. Another fundamental issue in providing support from orbit is the communication, especially for what concerns communications from Mars because of long delay of the signal. Communication capabilities from space assets in Mars orbits should be considered in order to strengthen the communication strategy.

*Functional Requirements* can be derived from the functions in the same ways as it was done in paragraph 3.2.1, i.e. converting the functions in "shall" statements.

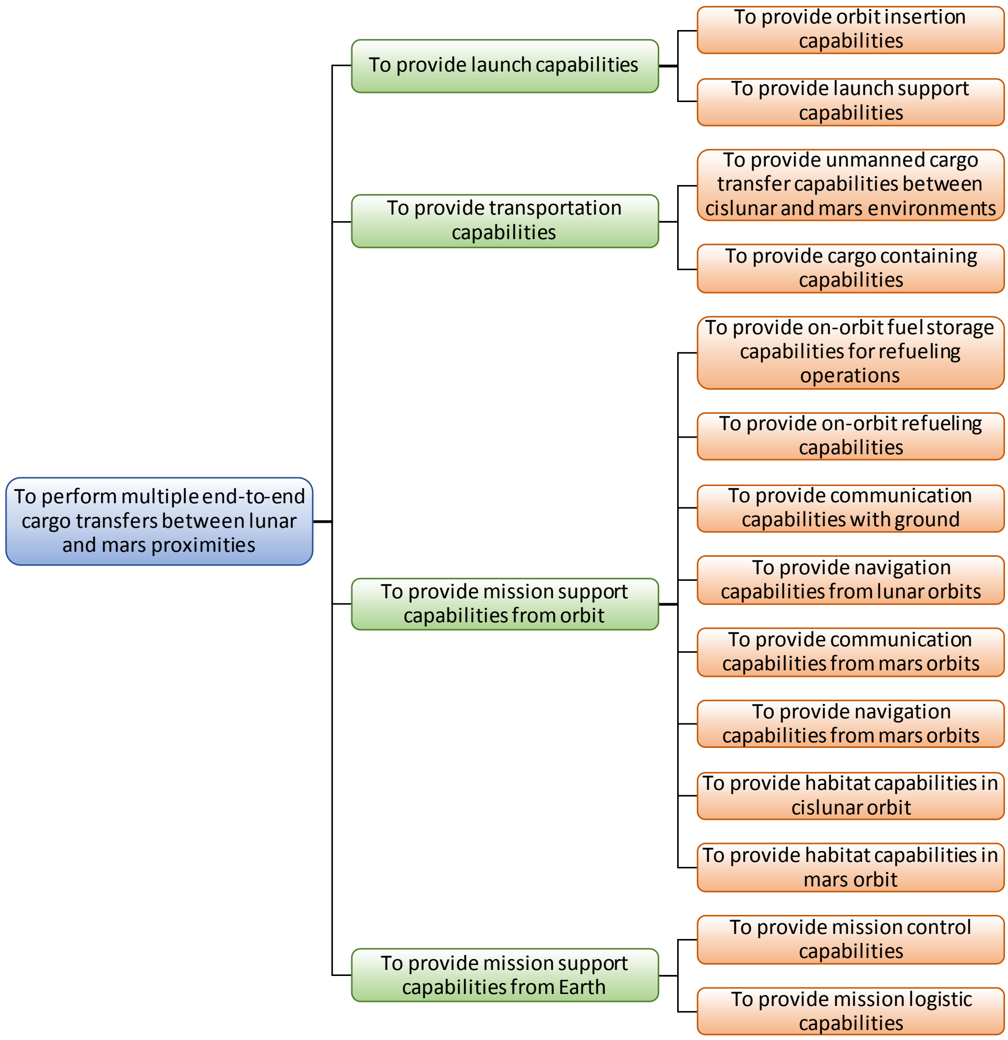


Figure 3.4: Functional Tree - System of Systems Level

Again, we have to allocate these functions to the elements able to perform them, which in this case are the Systems of the System of Systems architecture. The Functions/Products Matrix in Figure 3.5 highlights the matches between the function and the Systems. Systems identified constitute the Building Blocks of the functional architecture at System of Systems level, the main elements involved in the mission. They are described in Table 3.1.

| **Building Block** | **Description** |
|---|---|
| *Launch Vehicle* | The system in charge of inserting the ICV into the desired LEO orbit. |
| *Launch Control Station* | The facility necessary to handle and control launch operations from ground. |
| *ICV* | The Interplanetary Cargo Vehicle which has to transfer the payload and provide it with power generation, environmental protection and communications. |
| *Cargo Module* | The element containing the payload that has to be transferred from LOP-G to MOS. |
| *LOP-G* | The Lunar Orbital Platform-Gateway, a multi-modular habitable infrastructure operating in cislunar space where the ICV docks to be loaded up with cargo and where it is refueled. |
| *MOS* | The Mars Orbital Station, the Mars-orbiting habitable outpost needed to be provided with cargo to support its development, advancement and its operations. |
| *Lunar Navigation Satellites* | Satellites system that provides ICV with guidance and navigation service in cislunar environment. |
| *Mars Communication Satellites* | Orbital assets in Mars proximity that provide communications services to the ICV and back to Ground Segment. |
| *Mars Navigation Satellites* | Satellites system providing ICV with guidance and navigation service in mars proximities. |
| *Mission Control Center* | Ground facility providing systems control and monitoring mission execution. |
| *Mission Logistic Center* | Ground facility providing logistic services and information throughout the mission. |

Table 3.1: Building Blocks description

| | Systems | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | LS | | SS | | | | | | | GS | |
| Functions | Launch Vehicle | Launch Control Station | ICV | Cargo Module | LOP-G | MOS | Lunar Navigation Satellites | Mars Communication Satellites | Mars Navigation Satellites | Mission Control Center | Mission Logistic Center |
| To provide orbit insertion capabilities | X | | | | | | | | | | |
| To provide launch support capabilities | | X | | | | | | | | | |
| To provide unmanned cargo transfer capabilities between cislunar and mars environments | | | X | | | | | | | | |
| To provide cargo containing capabilities | | | | X | | | | | | | |
| To provide on-orbit fuel storage capabilities for refueling operations | | | | | X | | | | | | |
| To provide on-orbit refueling capabilities | | | X | | | | | | | | |
| To provide communication capabilities with ground | | | X | | | | | | | | |
| To provide navigation capabilities from lunar orbits | | | | | | | X | | | | |
| To provide communication capabilities from mars orbits | | | | | | | | X | | | |
| To provide navigation capabilities from mars orbits | | | | | | | | | X | | |
| To provide habitat capabilities in cislunar orbit | | | | | X | | | | | | |
| To provide habitat capabilities in mars orbit | | | | | | X | | | | | |
| To provide mission control capabilities | | | | | | | | | | X | |
| To provide mission logistic capabilities | | | | | | | | | | | X |

Figure 3.5: Functions/Products Matrix - System of Systems Level

Through the Functions/Products Matrix *Functional Requirements* can be refined: each previous "shall" statement now has to specify the element performing the task. Thus, for instance, *Orbit insertion capabilities shall be provided* becomes *Launch Vehicle shall provide orbit insertion capabilities.*

Through the matches highlighted in the Functions/Products Matrix in Figure 3.5 we lead the mission design to a specific direction, since we are forced to make choices between alternatives. Especially for what concerns the system associated with the function *To provide on-orbit fuel storage capabilities for refueling operations* two main viable options are possible. The task could be performed by the LOP-G, which is a system already foreseen in the functional architecture since it provides habitat capabilities in cislunar orbit or by a dedicated refueling system, i.e. a space system introduced specifically to enable ICV refueling operations. However,the alternative that has been considered for this study is the former one.

### 3.2.3 Functional Architecture at System of Systems Level

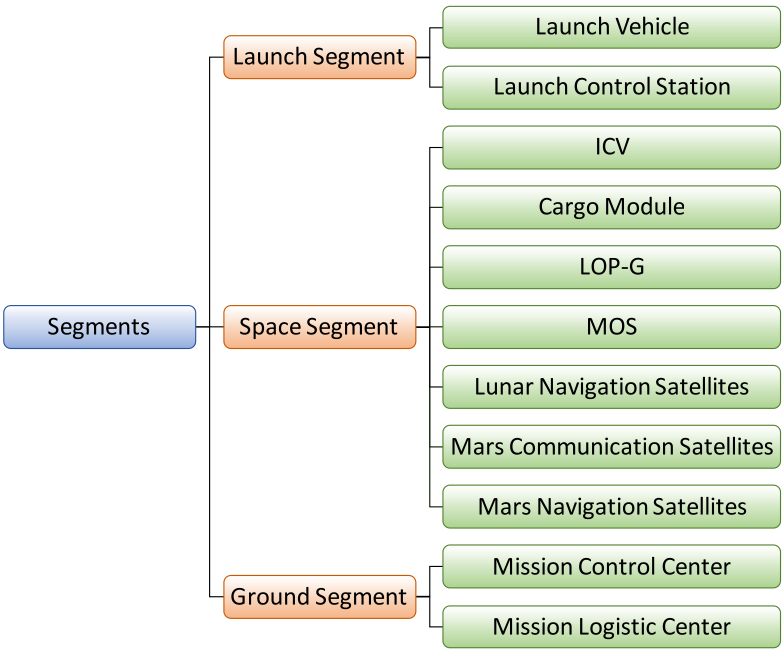



Figure 3.6: Product Tree - System of Systems Level

By simply grouping together the Building Blocks the Product Tree of the System of Systems Level in Figure 3.6 can be generated. Launch Vehicle and Launch Control Station are part of the Launch Segment, while ICV, Cargo Module, LOP-G, MOS, Lunar Navigation Satellites, Mars Communication and Mars Navigation

Satellites constitute the Space Segment. Eventually, Mission Control Center and Mission Logistic Center are the facilities belonging to the Ground Segment.

From the Product Tree *Configuration Requirements* can be derived. They provide indications about the architecture composition and internal organization. For instance, *The Ground Segment shall consist of the Mission Control Center and the Mission Logistic Center* is a configuration requirement.

Completing the functional architecture at System of Systems Level requires the determination of the connections between all the Building Block. The Connection Matrix in Figure 3.7 highlights which elements are interconnected while the Functional Block Diagram in Figure 3.8 provides additional information about the type of connections and their directionalities, especially from the ICV standpoint, which is the core system of the mission.

| | Launch Vehicle | Launch Control Station | ICV | Cargo Module | LOP-G | MOS | Lunar Navigation Satellites | Mars Communication Satellites | Mars Navigation Satellites | Mission Control Center | Mission Logistic Center |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Launch Vehicle | | | | | | | | | | | |
| Launch Control Station | X | | | | | | | | | | |
| ICV | X | | | | | | | | | | |
| Cargo Module | | | X | | | | | | | | |
| LOP-G | | | X | X | | | | | | | |
| MOS | | | X | X | | | | | | | |
| Lunar Navigation Satellites | | | X | | | | | | | | |
| Mars Communication Satellites | | | X | | | X | | | | | |
| Mars Navigation Satellites | | | X | | | | | | | | |
| Mission Control Center | | | X | | | | | X | | | |
| Mission Logistic Center | | | X | | | | | | | X | |

Figure 3.7: Connection Matrix - System of Systems Level

During the launch, the ICV is mechanically connected with the Launch Vehicle and sends its telemetry data to it, in order to be monitored by the Launch Control Station, which communicates with the Launch Vehicle. In orbit, the ICV receives data from Lunar Navigation Satellites and Mars Navigation Satellites to elaborate its position in both cislunar and Mars proximities. In Mars vicinity communication with the Mission Control Center occurs through the Mars Communication Satellites, which release the ICV from the high power required to detect and transmit signals back to Earth. The same is true for the MOS. The ICV also exchanges data with the MOS and the LOP-G to support rendezvous and mating operations with both stations. Initially, the mechanical link of the ICV with both LOP-G and MOS was considered, but, after developing the Concept of Operations analysis, the one with the MOS was removed, since the ICV is always attached to the Cargo Module when it is at the MOS and the mating interface is only between the Cargo Module and the MOS. At the LOP-G, instead, the mechanical link is always present, even if in different forms depending on the scenario considered among those developed in Chapter 5. A fluidic link exists between the ICV and the LOP-G as the ICV is refueled at the cislunar station. When transferring the Cargo Module, the ICV is not only mechanically attached to it but also provides it with power and receives from it telemetries to monitor its state of health.

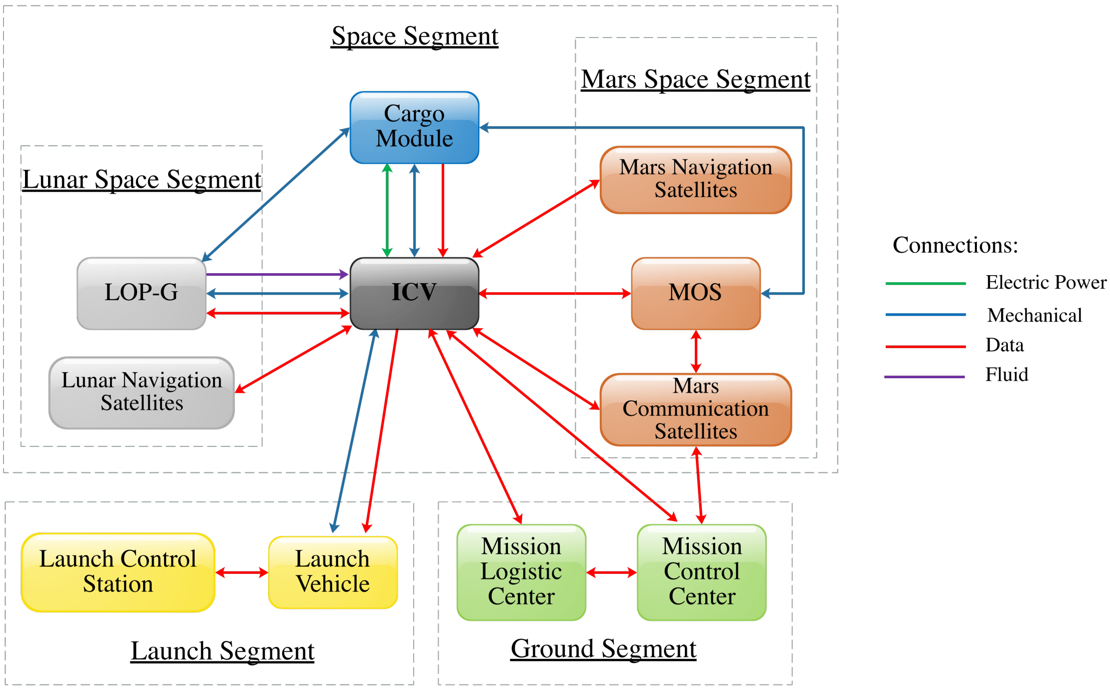



Figure 3.8: Functional Block Diagram - System of Systems Level

From the Connection Matrix *Interface Requirements* can be set down. They verbalize for each Building Block with which other elements shall it interface. For instance, *ICV shall interface with LOP-G* is an interface requirement deriving from the Connection Matrix. Interface Requirements are then refined after developing the Functional Block Diagram, i.e. new requirements are generated specifying types and directions of connections. Considering the previous example, the requirement is detailed in four new requirements:

1. *ICV shall mechanically interface with LOP-G*
2. *ICV shall transmit data to LOP-G*
3. *ICV shall receive data from LOP-G*
4. *ICV shall be supplied with fuel by LOP-G*

Now that all Systems constituting the groundwork of the mission architecture have been identified and their main relations determined, we will focus in the following chapter on the ICV system to provide its own functional characterization and determine how it should be internally arranged.

# Chapter 4

# Functional Analyses at System and Subsystem Levels

## 4.1 Functional Analysis at System Level

### 4.1.1 Subsystems Identification

To identify the elements which are part of the functional architecture at System Level, we first extent the Functional Tree of the previous level exclusively for what concerns the function assigned to the ICV, that were:

1. To provide unmanned cargo transfer capabilities between cislunar and Mars environments;

2. To provide communication capabilities with ground;

3. To provide on-orbit refueling capabilities.

These functions are the starting point for the definition of the Functional Tree at System Level and must be decomposed to obtain functions related to subsystems tasks. By asking how the ICV functions can be performed, we can simplify them obtaining the Functional Tree shown in Figure 4.1.

Several capabilities are required to perform the first function: propulsion, propellant management and power management are necessary to thrust the vehicle. Power management capabilities allow also providing electric power to the equipment on board the spacecraft. Guidance capabilities determine the desired path of travel and how to reach it. Navigation and control, respectively, resolve current state vector and determine the necessary thrust to get the spacecraft where

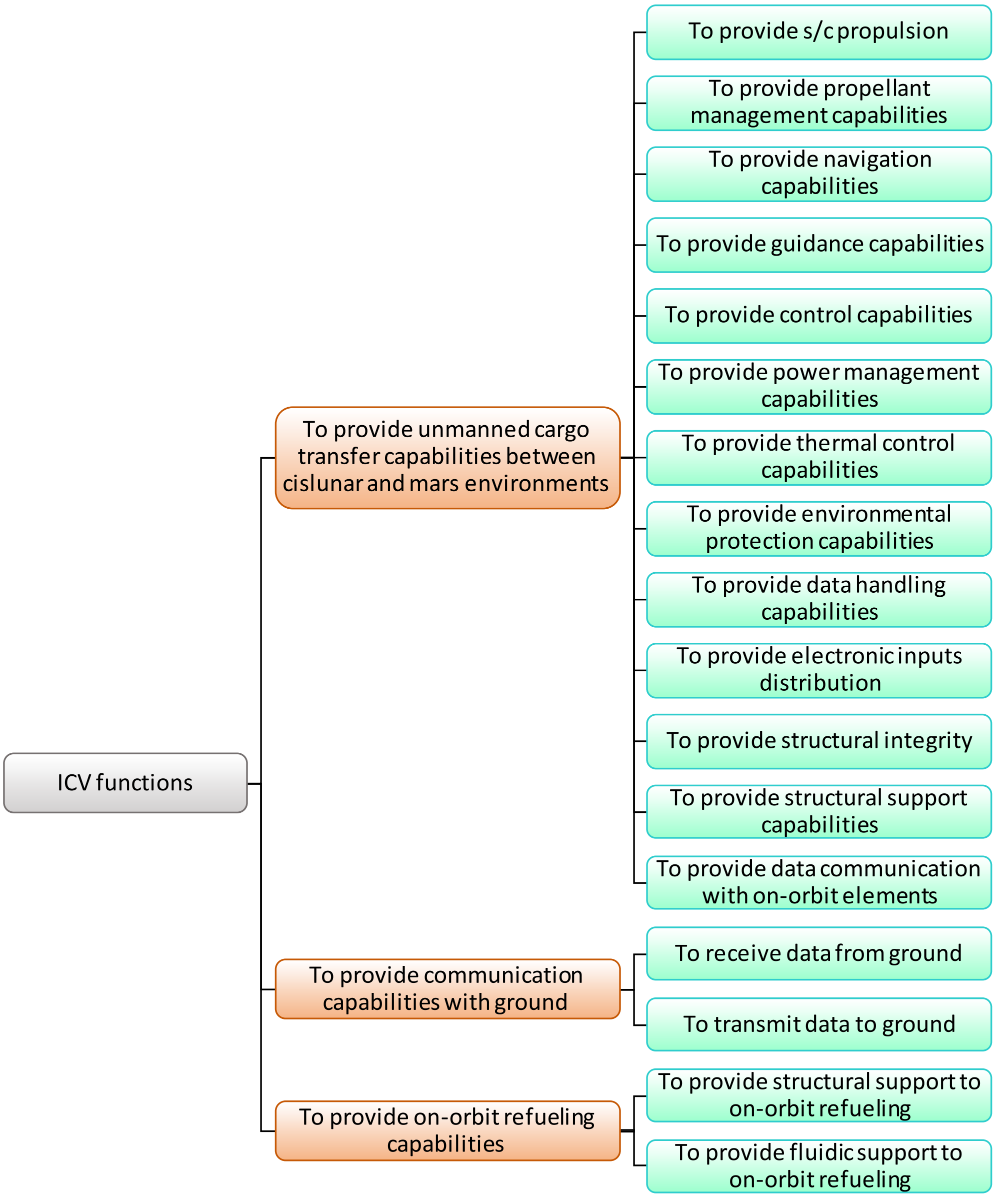



Figure 4.1: Functional Tree - Systems Level

it needs to go. Data handling capabilities deal with data collecting and distribution throughout the vehicle. Furthermore, transferring both power and data on the spacecraft requires electronic inputs distribution. To safely move in space the ICV also needs environmental protection and thermal control capabilities, as well as structural integrity capabilities to preserve internal volumes distribution and structural support capabilities to sustain spacecraft equipment in various mission phases. Data communication with on-orbit elements is necessary to interact with

| | | Subsystems | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | PROP | AOCS | EPS | DMS | TT&C | TCS | S&M | REF | HARN |
| Functions | To provide s/c propulsion | X | | | | | | | | |
| | To provide propellant management capabilities | X | | | | | | | | |
| | To provide navigation capabilities | | X | | | | | | | |
| | To provide guidance capabilities | | X | | | | | | | |
| | To provide control capabilities | | X | | | | | | | |
| | To provide power management capabilities | | | X | | | | | | |
| | To provide thermal control capabilities | | | | | | X | | | |
| | To provide environmental protection capabilities | | | | | | | X | | |
| | To provide data handling capabilities | | | | X | | | | | |
| | To provide electronic inputs distribution | | | | | | | | | X |
| | To provide structural integrity | | | | | | | X | | |
| | To provide structural support capabilities | | | | | | | X | | |
| | To provide data communication with on-orbit elements | | | | | X | | | | |
| | To receive data from ground | | | | | X | | | | |
| | To transmit data to ground | | | | | X | | | | |
| | To provide structural support to on-orbit refueling | | | | | | | | X | |
| | To provide fluidic support to on-orbit refueling | | | | | | | | X | |

Figure 4.2: Functions/Products Matrix - System Level

the other space systems constituting the mission architecture and identified in Chapter 3.

For the second function both reception from ground and transmission to ground shall be ensured. To perform the third function it should be considered that a mechanical interface providing both fluidic and structural support is required to carry out refueling operations.

The Functions/Products Matrix shown in Figure 4.2 allows the identification of the following subsystems:

| **Subsystem** | **Description** |
|---|---|
| *PROP* | The *Propulsion Subsystem* provides thrust to adjust orbit and attitude and to manage angular momentum. |
| *AOCS* | The *Attitude and Orbit Control Subsystem* provides determination and control of attitude and orbital position. It stabilizes and orients the vehicle, providing pointing of the spacecraft and its appendages, such as antennas and solar arrays. |
| *EPS* | The *Electrical Power Subsystem* supplies spacecraft equipment with electric power. It generates and stores electric power, regulates and distributes it throughout the spacecraft. |
| *DMS* | The *Data Management Subsystem* validates and distributes command data and collects and formats telemetry data for the downlink. It also provides data storage. |
| *TT&C* | The *Tracking Telemetry and Command Subsystem* provides communication with ground facilities and other spacecrafts. It allows performing spacecraft tracking by retransmitting received range tones or by providing coherence between received and transmitted signals. |
| *TCS* | The *Thermal Control Subsystem* maintains equipment within allowable temperature limits for each mission phase. |
| *S&M* | The *Structures and Mechanisms Subsystem* provides the support structure to carry and protect spacecraft equipment. It includes mechanical interfaces with on-orbit systems. |
| *REF* | The *Refueling Subsystem* provides mechanical and fluidic couplings necessary to carry out refueling operations at the LOP-G. |
| *HARN* | The *Harness Subsystem* consists of all wiring, electronics backplane and electric interface boards to distribute data and provide electric power distribution. |

Table 4.1: Subsystems description

*Functional Requirements* can be derived from the Functional Tree and refined through the Functions/Products Matrix as indicated in Paragraph 3.2.2 for the System of Systems Level. Since more details are available with every level of the Functional Analysis, more specific functions are now expressed in the Functional Requirements. Therefore, Performance Requirements can be introduced to describe quantitatively how well those functions must be performed. Table 4.2 provides examples of Performance Requirements deriving from Functional Requirements. Numerical values are indicated with "TBD", meaning that they're yet to be defined in subsequent in-depth system sizing.

| ***Functional Requirements*** | ***Performance Requirements*** |
|---|---|
| *PROP shall provide spacecraft propulsion* | *PROP shall provide TBD Ns of total impulse;*<br>*PROP shall provide TBD N of thrust level* |
| *PROP shall provide propellant management capabilities* | *PROP shall manage TBD kg of propellants* |
| *AOCS shall provide control capabilities* | *AOCS shall provide TBD° of control accuracy;*<br>*AOCS shall provide TBD rad/s of speed of response;*<br>*AOCS shall provide TBD Nm of torque capability* |
| *EPS shall provide power management capabilities* | *EPS shall provide power to operate the equipment in compliance with power requirements for every mission phase* |
| *TCS shall provide thermal control capabilities* | *TCS shall maintain equipment within operative temperatures* |
| *TT&C shall provide data communications with on-orbit elements* | *TT&C shall receive data at a rate of TBD bit/s from on-orbit elements;*<br>*TT&C shall transmit data at a rate of TBD bit/s to on-orbit elements;*<br>*TT&C shall detect signal from on-orbit elements within TBD allowable error rate* |
| *DMS shall provide data handling capabilities* | *DMS shall transmit data at rates that supports command and telemetry requirements at any mission phase* |
| *HARN shall provide electronic inputs distribution* | *HARN shall dissipate power not exceeding TBD % of operating power* |

*Continued on next page*

| ***Functional Requirements*** | ***Performance Requirements*** |
|---|---|
| *S&M shall provide structural integrity* | *S&M shall guarantee fundamental frequencies of the S/C within the requirements of the Launch Vehicle to avoid dynamic coupling;* <br> *S&M shall support the mechanical static and dynamic loads encountered during ICV entire lifetime, including: ground operations, launch, deployment and on-orbit operations* |
| *REF shall provide fluidic support to on-orbit refueling* | *REF shall ensure correct couplings between the ICV and the LOP-G refueling port* |

Table 4.2: Examples of Performance Requirements deriving from Functional Requirements

### 4.1.2 Functional Architecture at System Level

Since the ICV is constituted by all the subsystems identified, its Product Tree easily results as represented in Figure 4.3.

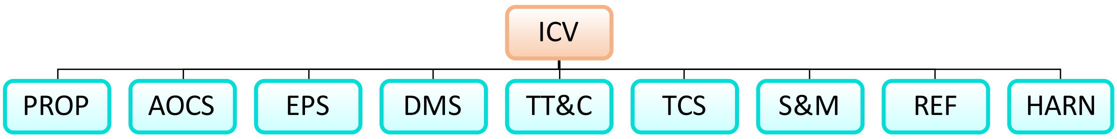



Figure 4.3: Product Tree - System Level

To properly interconnect all the subsystems determined, it is necessary to understand the essential needs that should be satisfied to make them work.

The PROP, AOCS, TCS, REF, TT&C and DMS subsystems all need to be supplied with electric power by the EPS. The PROP subsystem exploits electric power to generate thrust. The AOCS needs electric power for controllers, in charge of processing the ICV's attitude and orbit position, and for actuators, which are asked to change attitude and orbit position. The TCS subsystem also includes controllers to monitor equipment temperatures and electrical devices to control them. The REF subsystem requires electric power to handle couplings and valves between the ICV and the LOP-G for refueling operations. The TT&C needs electric power for transmitting and receiving devices, whereas the DMS for the central processor and data handling equipment.

The DMS gathers telemetries from the other subsystems and it formats them for the downlink. It needs to interface with the TT&C, to which it delivers the telemetry data and from which it receives commands. DMS then distribute commands to other subsystems. TT&C is in charge of transmitting telemetries received from the DMS to ground. Furthermore, it also has to receive and validate command data flowing from ground and from various on-orbit systems to the ICV.

The HARN includes all wirings allowing both data and power distributions while the S&M provides structural support and sustainment to all other subsystems. Eventually, one last connection can be identified at this level: it is the fuel flowing from the REF to the PROP during refueling operations.

In view of these considerations, the Connection Matrix and the Functional Block Diagram are those of Figures 4.4 and 4.5.

| | PROP | AOCS | EPS | DMS | TT&C | TCS | S&M | REF | HARN |
|---|---|---|---|---|---|---|---|---|---|
| PROP | | | | | | | | | |
| AOCS | | | | | | | | | |
| EPS | X | X | | | | | | | |
| DMS | X | X | X | | | | | | |
| TT&C | | | X | X | | | | | |
| TCS | | | X | X | | | | | |
| S&M | X | X | X | X | X | X | | | |
| REF | X | | X | X | | | | | |
| HARN | X | X | X | X | X | X | X | X | |

Figure 4.4: Connection Matrix - System Level

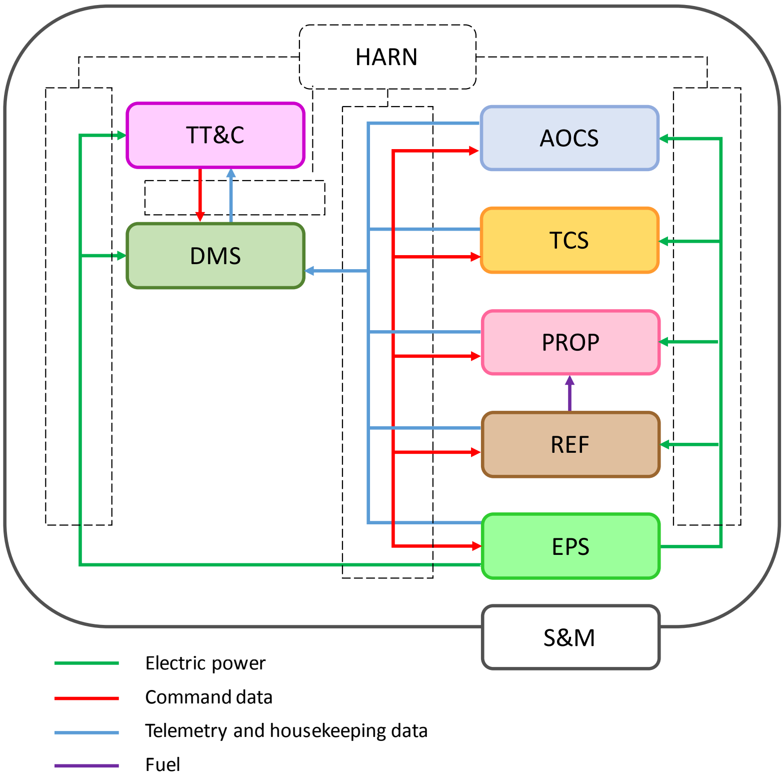



Figure 4.5: Functional Block Diagram - System Level

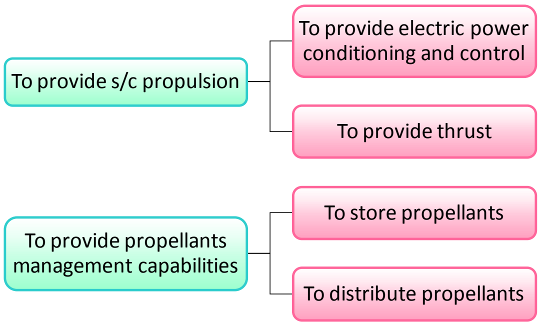
## 4.2 Functional Analysis at Subsystem Level

The definition of the next lower layer of the ICV architecture requires going further in the decomposition of the basic functions determined in the previous level. For each subsystem, the analysis leads to identify the main equipment, i.e. the fundamental elements which are necessary to perform the subsystem top-level function. In the following paragraphs, the components identification is given for each subsystem. After identifying all components of all subsystems, the functional architecture for the Subsystem Level as a whole is presented at the end of this section.

### 4.2.1 Propulsion Subsystem

The PROP subsystem is responsible for providing spacecraft propulsion and propellant management capabilities. To fulfill these tasks, the basic functions that shall be ensured are indicated in the Functional Tree in Figure 4.6. Elements able to perform them are shown in the Functions/Product Matrix on the right side of the figure. They include:

- Power Processing Unit (PPU)
- Thruster Units
- Fuel Tanks
- Feeding System




| | | PROP | | | |
|---|---|---|---|---|---|
| | | PPU | Thruster Units | Fuel Tanks | Feeding System |
| Functions | To provide electric power conditioning and control | X | | | |
| | To provide thrust | | X | | |
| | To store propellants | | | X | |
| | To distribute propellants | | | | X |

Figure 4.6: Functional Tree (left) and Functions/Products Matrix (right) - PROP

Thruster Units are in charge of providing thrust, each of them consists of a high-power Hall Effect Thruster (HET) and at least one high-current hollow cathode. In the Electric Propulsion, Hall Effect Thrusters have the advantage of operating with a high value of thrust to power ratio compared to the Gridded Ion Engines (GIEs). They use crossed electric and magnetic fields to generate and accelerate ions. The magnetic field traps electrons emitted by the hollow cathode, retarding their flow to the anode, so that they can collide with the neutral propellant ionizing it. The generated ions are then accelerated by the electric field. Considering the latest technological achievements, we can assume for a single thruster a thrust of $1000 mN$ and a Specific Impulse of $2500 s$.

The PPU is used to generate the electrical discharge between the cathode and the annular anode through which the propellant, usually Xenon, is injected. It also supplies power to coils to obtain the magnetic field. The PPU provides electric power conditioning and control in response to the thruster performances. It is supplied by the spacecraft's Power Conditioning and Distribution Unit (PCDU), part of the Electrical Power Subsystem. The On-Board Computer (OBC) is responsible for PPU control: it receives housekeeping data from the PPU and transmits commands to it.

High-pressure Xenon is stored in Fuel Tanks and it is supplied via the Feeding System to the Thruster Units. The standard Feeding System for Electric Propulsion applications employs a pressure regulator to manage the propellant pressure to a constant pressure over mission life. After the regulation of the pressure, the propellant is fed to the thrusters and controlled by the PPU. The PPU adjusts the anode voltage according to the thrust required by the OBC. As the PPU, also the Feeding System exchanges telemetries and command data with the OBC through Remote Interface Units (RIUs). OBC and RIUs are part of the Data Management Subsystem.

The Functional Block Diagram in Figure 4.7 illustrates PROP components interconnections and links with components from other subsystems.

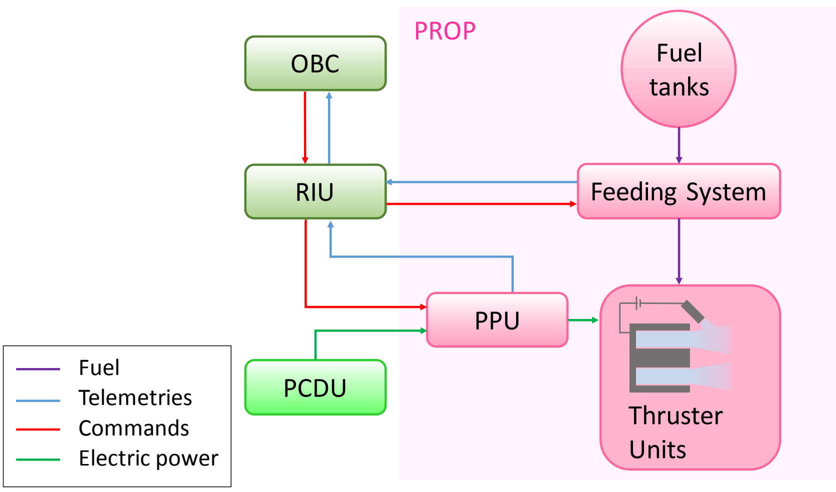


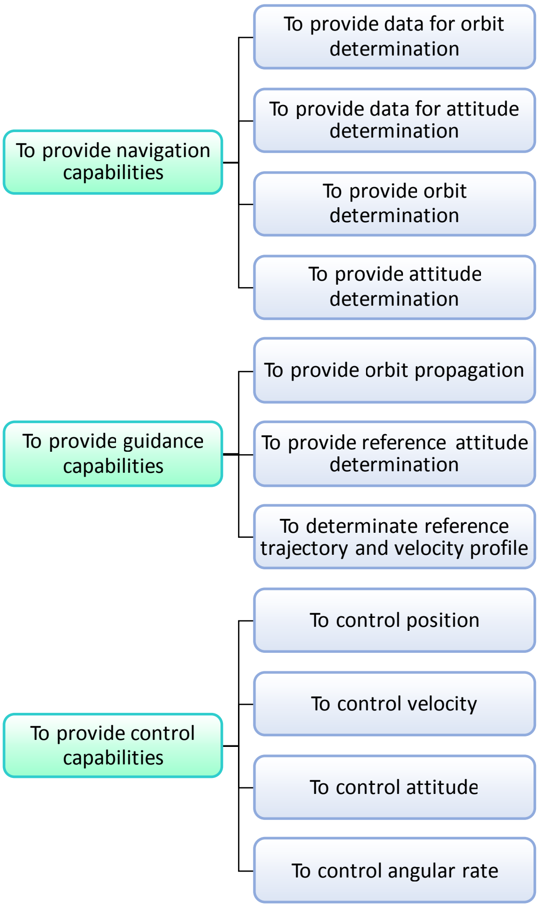

Figure 4.7: Functional Block Diagram - PROP

### 4.2.2 Attitude and Orbit Control Subsystem

The AOCS subsystem shall ensure navigation, guidance and control capabilities. To perform these tasks, the basic functions that shall be provided are indicated in the Functional Tree in Figure 4.9. Components able to perform the AOCS basic functions are identified through the Functions/Products Matrix illustrated in Figure 4.9 on the right side. They are:

- Orbit Sensors

- Attitude Sensors
- AOCS On-Board Computer (AOCS OBC)
- AOCS Actuators




| Functions | AOCS: Orbit Sensors | AOCS: Attitude Sensors | AOCS: AOCS Actuators | AOCS: AOCS OBC |
|---|---|---|---|---|
| To provide data for orbit determination | X | | | |
| To provide data for attitude determination | | X | | |
| To provide orbit determination | | | | X |
| To provide attitude determination | | | | X |
| To provide orbit propagation | | | | X |
| To provide reference attitude determination | | | | X |
| To determinate reference trajectory and velocity profile | | | | X |
| To control position | | | X | |
| To control velocity | | | X | |
| To control attitude | | | X | |
| To control angular rate | | | X | |

Figure 4.8: Functional Tree (left) and Functions/Products Matrix (right) - AOCS

Orbit Sensors and Attitude Sensors provide measurements for navigation. Navigation deals with the determination, at a given time, of the spacecraft's attitude and orbit position. The AOCS OBC processes measurements from sensors to reconstruct both orbit and orientation of the ICV.

The AOCS OBC uses algorithms to propagate orbits and generates and tracks relative guidance trajectory. Besides determining the desired trajectory from the ICV's current location to a designated target, it also define changes in velocity for following that path. Furthermore, it determine the reference attitude that the ICV has to follow to satisfy pointing requirements, such as those for communications antennas and solar arrays.

The AOCS Actuators allow forces manipulation in order to follow both the desired trajectory and reference attitude. AOCS Actuators are consequently in charge of control both position and velocity as well as attitude and angular rate. As shown in Figure 4.9 they receive commands from the AOCS OBC, via a RIU, after the sensor telemetries elaboration.

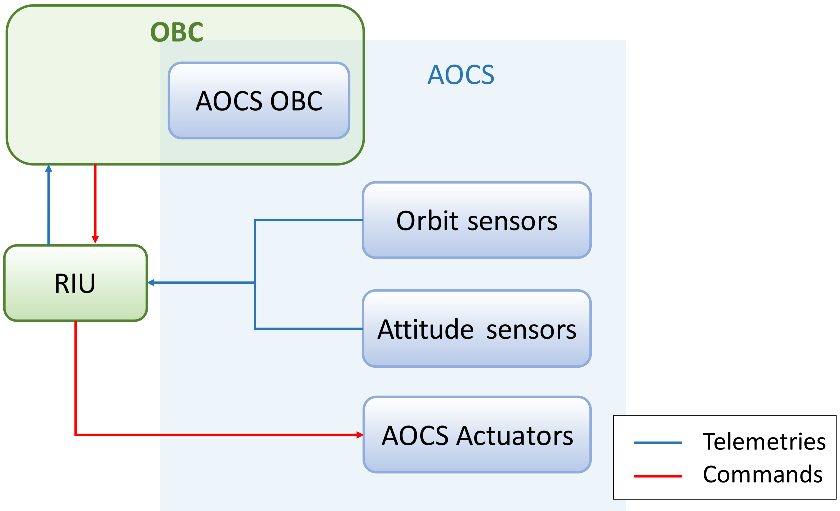


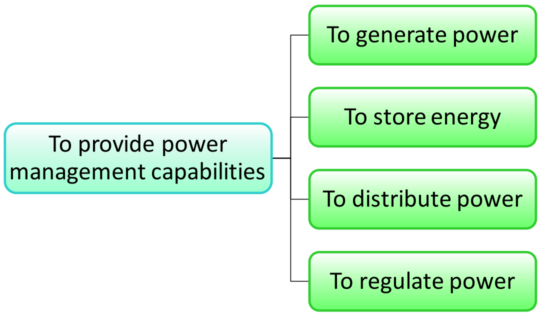

Figure 4.9: Functional Block Diagram - AOCS

### 4.2.3 Electrical Power Subsystem

The EPS is in charge of providing power management capabilities. This means it has to generate power, to store energy and to provide power regulation and distribution, as indicated in the Functional Tree in Figure 4.10. Allocating these functions to components produce the Functions/Products Matrix on the right side of the figure. A basic architecture for the EPS consists of:

- Solar Arrays
- Batteries
- Power Conditioning and Distribution Unit (PCDU)

Solar Arrays provides conversion of Sun energy into usable electrical power for the entire spacecraft. Once electrical energy is obtained, it has to be stored




| Functions | EPS: Solar Arrays | EPS: Batteries | EPS: PCDU |
|---|---|---|---|
| To generate power | X | | |
| To store energy | | X | |
| To distribute power | | | X |
| To regulate power | | | X |

Figure 4.10: Functional Tree (left) and Functions/Products Matrix (right) - EPS

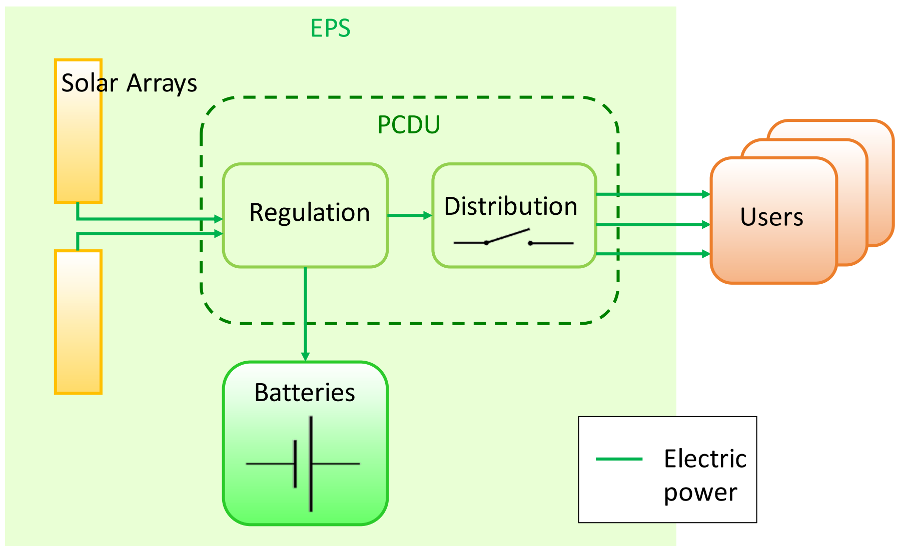



Figure 4.11: Functional Block Diagram - EPS

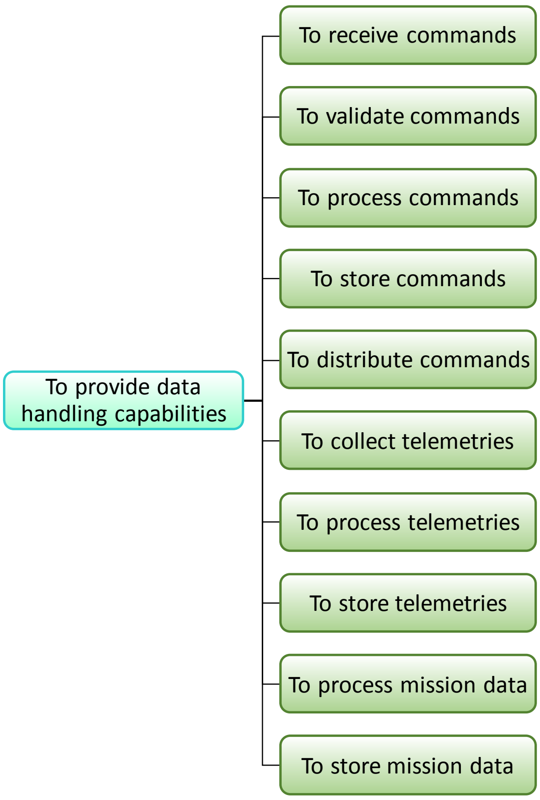
in batteries, to be used when the ICV is in shadow. Electric power has to be distributed to the various subsystems with a defined regulation. This last task is performed by the Power Conditioning and Distribution Unit (PCDU).

In fact, the PCDU shall condition, control, and distribute electrical energy during each ICV mission phases in according with the requirements of the various primary power users of the spacecraft. Furthermore, it shall regulate power from Solar Arrays for battery charging and shall provide switching that allows the batteries to supply power when needed. It is also expected to provide protection against short circuits and to isolate faults.

Functional Block Diagram in Figure 4.11 shows how EPS components can be arranged.

### 4.2.4 Data Management Subsystem

The DMS is responsible for data management. To simplify this task, decomposition of the DMS top function is provided in the Functional Tree in Figure 4.12.




| Functions | DMS: Commands Decoder | DMS: OBC | DMS: Data Storage Unit | DMS: RIU |
|---|---|---|---|---|
| To receive commands | X | | | |
| To validate commands | X | | | |
| To process commands | | X | | |
| To store commands | | | X | |
| To distribute commands | | | | X |
| To collect telemetries | | | | X |
| To process telemetries | | X | | |
| To store telemetries | | | X | |
| To process mission data | | X | | |
| To store mission data | | | X | |

Figure 4.12: Functional Tree (left) and Functions/Products Matrix (right) - DMS

Through the Functions/Products Matrix in Figure 4.12 the DMS basic functions are matched with the following components:

- Commands Decoder
- On-Board Computer (OBC)

- Data Storage Unit
- Remote Interface Unit (RIU)

The Commands Decoder acts as a filter rejecting messages that do not pass validation criteria. validated commands are processed in the OBC and can either be stored in the Data Storage Unit to be executed later, in this case they are associated to timer-execute commands, or they can be delivered directly to the users, through RIUs, as indicated in the Functional Block Diagram in Figure 4.13.

A RIU (also called RTU: Remote Terminal Unit) is a unit usually present on medium-large size spacecraft and represents an example of distributed control system implementation. It offloads the OBC from analogue and digital data acquisition and from actuators control tasks. Through RIUs telemetries from various users are gathered to be elaborated and formatted in the OBC with other mission data.

The DMS interfaces with the TT&C subsystem from which it receives commands and to which it sends the formatted telemetry stream.

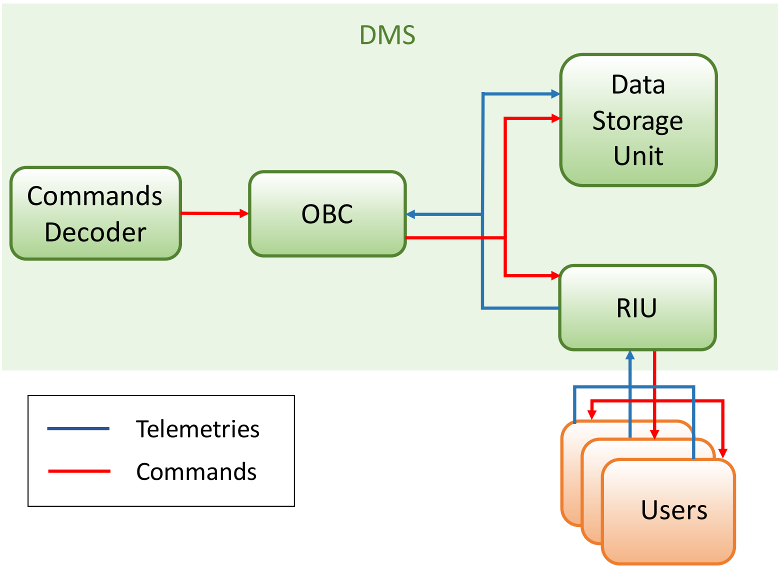
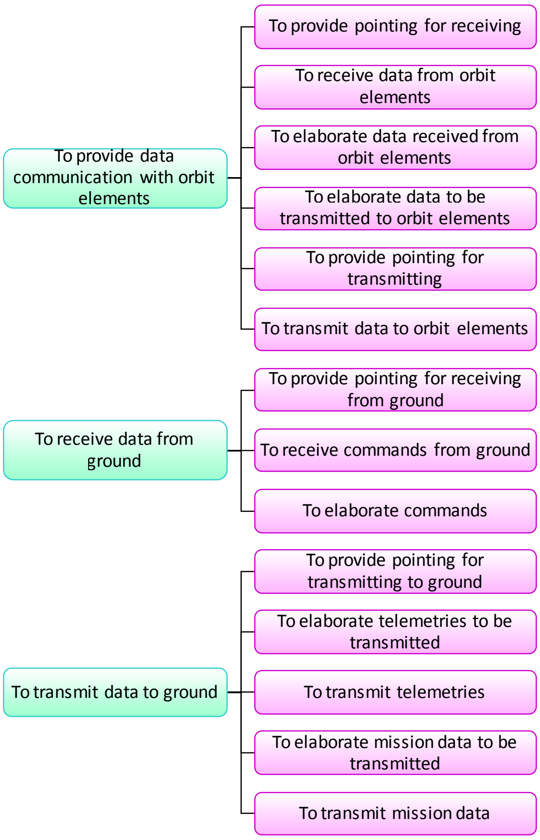



Figure 4.13: Functional Block Diagram - DMS

### 4.2.5 Tracking, Telemetry and Command Subsystem

The TT&C subsystem has to provide communication with on-orbit elements and with ground. These tasks have been simplified through the decomposition




| | | TT&C | | | |
|---|---|---|---|---|---|
| | | Antennas | Receiver | Transmitter | Auto-tracking equipment |
| Functions | To provide pointing for receiving | | | | X |
| | To receive data from orbit elements | X | | | |
| | To elaborate data received from orbit elements | | X | | |
| | To elaborate data to be transmitted to orbit elements | | | X | |
| | To provide pointing for transmitting | | | | X |
| | To transmit data to orbit elements | X | | | |
| | To provide pointing for receiving from ground | | | | X |
| | To receive commands from ground | X | | | |
| | To elaborate commands | | X | | |
| | To provide pointing for transmitting to ground | | | | X |
| | To elaborate telemetries to be transmitted | | | X | |
| | To transmit telemetries | X | | | |
| | To elaborate mission data to be transmitted | | | X | |
| | To transmit mission data | X | | | |

Figure 4.14: Functional Tree (left) and Functions/Products Matrix (right) - TT&C

of TT&C top level functions, as shown in the Functional Tree in Figure 4.14 The subsystem is responsible for receiving and demodulating signals from ground and from on-orbit systems, as well as modulating and transmitting signals to ground and on-orbit systems. The subsystem also allows to track the spacecraft by retransmitting received range tones or providing coherence between received and transmitted signals.

The basic elements of the TT&C Subsystem identified in the Functions/Products Matrix of Figure 4.14 are:

- Antennas
- Receiver
- Transmitter

- Auto-tracking equipment

The Antenna is the device that transmits and receives signals. In transmission, the antenna radiates energy from the current supplied by the Transmitter in form of electromagnetic waves. In reception, conversely, it intercepts power of electromagnetic wave in order to produce an electric current that is then transmitted to the Receiver. The ability to communicate requires clear field of view for the ICV antennas and sufficient received power to detect the signal with acceptable error rate. The antennas are expected to provide pointing for receiving and transmitting data with the various systems and facilities with which the ICV has to communicate.

Auto-tracking equipment performs closed-loop antenna pointing by generating error signal for the AOCS Subsystem, so it can point the antenna, as indicated in Figure 4.15.

The Transmitter provides modulation and amplification of the signal to be transmitted. The modulation is the process of varying a carrier signal properties with a baseband signal that contains information to be transmitted. The signal so obtained is the "modulated signal" and has to be amplified prior transmission.

The Receiver deals with the amplification of the received signal and its demodulation, i.e. the extraction of the original information-bearing signal from the carrier wave.

Functional Block Diagram in Figure shows TT&C components and their connections.

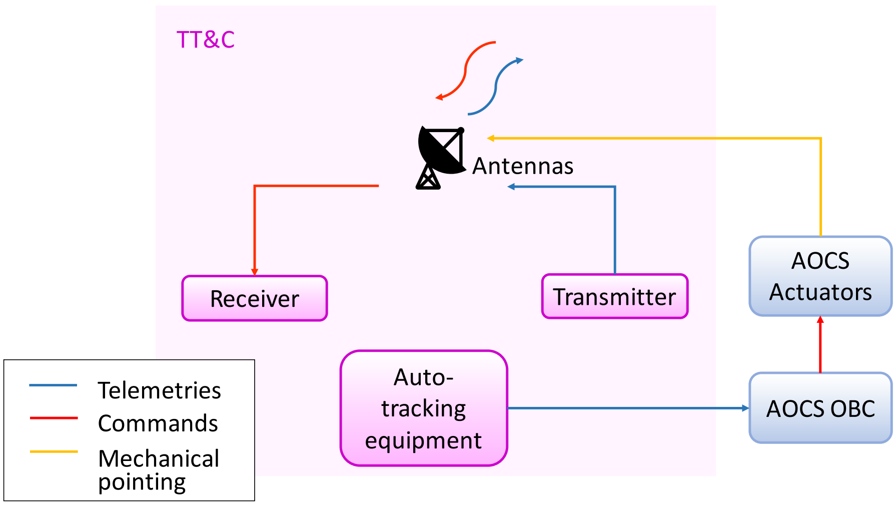



Figure 4.15: Functional Block Diagram - TT&C

### 4.2.6 Thermal Control Subsystem

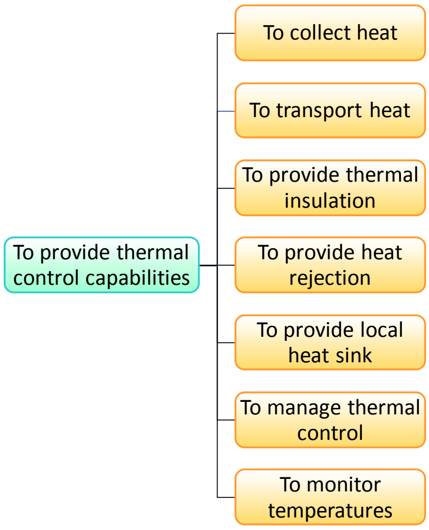
The TCS top function has been extended in the Functional Tree in Figure 4.16. The subsystem is in charge of maintaining all ICV components and subsystem within their required temperature limits during the whole mission. It has also to ensure that temperature gradient requirements are met to minimize thermal distortion. The thermal control techniques must cope with the external environment, which can vary in a wide range, as the spacecraft is exposed to deep space, or to solar or planetary flux. Furthermore, it has to reject the internal heat generated by the operation of the spacecraft itself. Thermal control techniques are used to protect the equipment from overheating and from too cold temperature and can be either passive or active. Passive techniques requires no input power for thermal regulation, they make use of materials, surface finishes and coatings to strike a balance between the heat absorbed and the heat radiated to space. Active thermal control is necessary for components that have stringent temperature requirements or which dissipate large amount of electrical power. It maintains the temperatures by means of electrical devices such as electrical heaters or thermo-electric coolers.

Components identified through the Functions/Products Matrix in Figure 4.16 are:

- Heat Pipes
- Multilayer Insulation Blankets (MLI Blankets)
- Radiators
- Electrical Heaters
- TCS On-Board Computer (TCS OBC)
- Temperature Sensors

Heat pipes are used to collect heat from localized sources and transport it to radiators where it is rejected. If heat pipes are used, it is therefore not necessary to mount all components to be cooled directly on radiator panels. A heat pipe is a passive thermal control technique that uses a closed two-phase fluid-flow cycle to transport large quantities of heat without the use of electrical power.

MLI blankets are other common passive technique for thermal insulation. Most spacecraft are covered with them except on radiator that, instead, have to reject internally generated heat. MLI blankets are composed of multiple layers of low-emittance film with low conductivity between the layers. They are typically used to protect internal propellant tanks and propellant lines.




| Functions | Heat Pipes | MLI Blankets | Radiators | Electrical Heaters | TCS OBC | Temperature Sensors |
|---|---|---|---|---|---|---|
| To collect heat | X | | | | | |
| To transport heat | X | | | | | |
| To provide thermal insulation | | X | | | | |
| To provide heat rejection | | | X | | | |
| To provide local heat sink | | | | X | | |
| To manage thermal control | | | | | X | |
| To monitor temperatures | | | | | | X |

Figure 4.16: Functional Tree (left) and Functions/Products Matrix (right) - TCS

Radiators are panels that provide spacecraft's waste heat rejection by infrared (IR) radiation from their surfaces. Sources of heat for the ICV include solar radiation, planetary reflection and IR radiation, electrical energy dissipated in electrical components, impingement of plume from thrusters on the external surfaces of the spacecraft.

Electrical heaters are used either to protect components from getting too cold or to make up for heat that is not dissipated in a electric component after it is turned off. They commonly consist of an electrical resistance element arranged between two sheets of electrically insulating material. They are coupled with sensors and controllers to provide very precise temperature control.

The TCS OBC is the processing unit in charge of control electrical heaters: it reads temperature from telemetry sensors and sends signals to turn heaters on and off through a RIU.

Temperature sensors provide the TCS OBC with temperature measurements. They are in the form of integrated circuits and exploit the temperature-sensitive voltage vs. current characteristics of semiconductor diodes. By exciting the sensor via a known current, it is possible to correlate the sensor's analog voltage level into a temperature measure.

The TCS Functional Block Diagram in Figure 4.17 shows the schematic arrangement of the TCS components in relation to the equipment whose temperature has to be controlled.

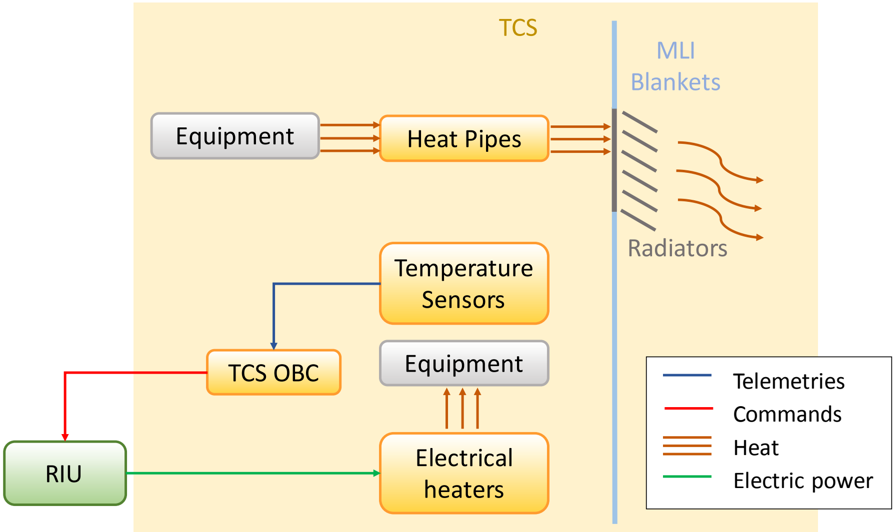


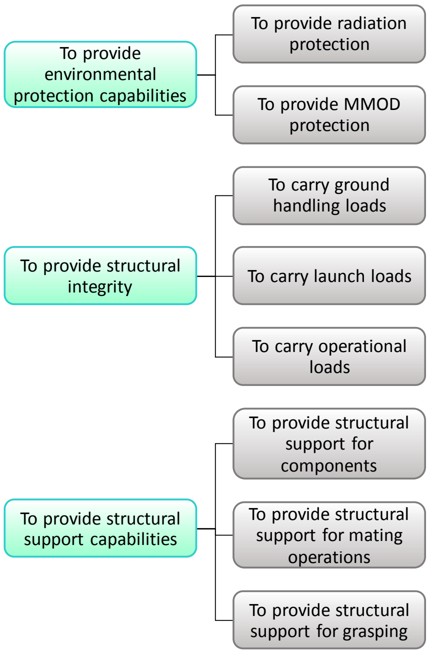

Figure 4.17: Functional Block Diagram - TCS

### 4.2.7 Structures and Mechanisms

The S&M subsystem provides structural support to sustain subsystems and components in each mission phase and during different mission operations. It preserve the structural integrity of the ICV and protect it from the external environment, with special attention to space radiation. These functions can be divided in low level function as indicated in the Functional Tree in Figure 4.18. Components performing these tasks are identified in the Functions/Products Matrix on the right side of the figure. They are:

- Radiation Shields
- Primary Structure
- Secondary Structure
- Meteoroid/Debris Protection System Panels (MDPS Panels)
- Docking Interface (Docking I/F)
- Grasping Interface (Grasping I/F)

Radiation Shields are barriers aimed to isolate electrical devices and cables from radiation damage caused by charge particles. Charged particles are present in space and carry enough energy to liberate electrons from atoms, creating electrical charges concentration and undesirable electric fields inside the semiconductor materials. Source for these particles are:




| | | S&M | | | | | |
|---|---|---|---|---|---|---|---|
| | | Radiation Shields | MDPS Panels | Primary Structure | Secondary Structure | Docking I/F | Grasping I/F |
| Functions | To provide radiation protection | X | | | | | |
| | To provide MMOD protection | | X | | | | |
| | To carry ground handling loads | | | X | | | |
| | To carry launch loads | | | X | | | |
| | To carry operational loads | | | X | | | |
| | To provide structural support for components | | | | X | | |
| | To provide structural support for mating operations | | | | | X | |
| | To provide structural support for grasping | | | | | | X |

Figure 4.18: Functional Tree (left) and Functions/Products Matrix (right) - S&M

- Solar Particle Events (SPEs): energetic protons emitted during the coronal mass ejection of the Sun;
- Galactic Cosmic Rays: high-energy particles coming from outside the Solar System;
- Van Allen radiation belts: energetic particles confined around the Earth's magnetic field lines.

The Primary Structure represent the main load-carrying structure. It shall support the mechanical static and dynamic loads encountered during ICV entire lifetime, including: ground operations, launch, deployment and on-orbit operations. This structure provides the attachments with the Cargo Module and the Launch Vehicle.

The Secondary Structure consists of deployables and supports for components and is attached to the primary structure, to which it transfers loads.It provides mounting provisions for solar arrays and antennas and supports wire bundles, propellant lines, non-structural doors, and brackets for components.

The ICV will be exposed to natural meteoroids and man-made orbital debris, impacting at hypervelocity at the vehicle surface during the mission. Both can cause severe damage to the Primary Structure and subsystems.The MPDS Panels act as bumper-panels: they decelerate the impacting particles and, depending on mass and velocity, they can fragment, melt and vaporize them. MPDS panels are made of metallic sheets and are fixed to the Primary Structure.

The Docking I/F is a mating mechanism that supports docking operations at the standardized docking ports the ICV shall interface with during the mission. The mission scenarios analysis developed in Chapter 5 brings out the need of a Docking I/F to mate with the Cargo Module and, in one of the two scenarios, also with the LOP-G.

The Grasping I/F is a mechanism that allow the ICV to be grabbed by a robotic arm. The need for a Grasping I/F arise in one of the two scenarios analyzed in Chapter 5.

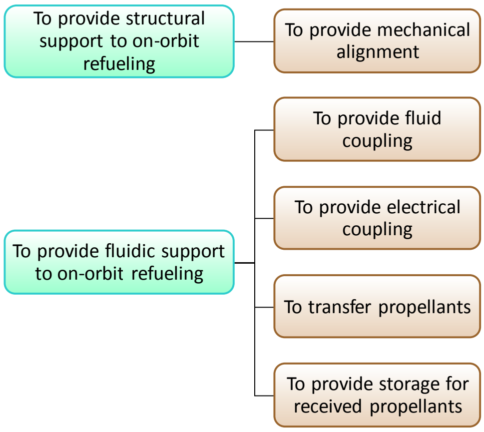
### 4.2.8 Refueling Subsystem

The REF subsystem shall provide structural and fluidic support to on-orbit refueling. These functions have been decomposed in simpler functions in the Functional Tree shown in Figure 4.19. Through the Functions/Products Matrix on the right side, the following refueling provisions have been identified:

- Fluid Plane
- Fluid Couplings
- Electrical Connector
- Refueling Valves
- Refueling Tanks

The Fluid Plane is a mechanical plate intended to guide the correct alignment between the ICV and the LOP-G refueling interfaces. It provides the mounting structure for the Fluid Couplings and the Electrical Connector. The Fluid Couplings represent the fluid connections for propellants. Once they've been connected with the equivalent couplings on the LOP-G, they allow fuel transfer from the servicing system to the ICV. The Electrical Connector provides the electrical link between the ICV and the station. Electric power is used to operate the Refueling Valves, which transfer the fuel in the Refueling Tanks.

Figure 4.20 illustrates the Functional Block Diagram for the REF subsystem.




| Functions | REF: Fluid Plane | Fluid Couplings | Electrical Connector | Refueling Valves | Refueling Tank |
|---|---|---|---|---|---|
| To provide mechanical alignment | X | | | | |
| To provide fluid coupling | | X | | | |
| To provide electrical coupling | | | X | | |
| To transfer propellant | | | | X | |
| To provide storage for received propellant | | | | | X |

Figure 4.19: Functional Tree (left) and Functions/Products Matrix (right) - REF

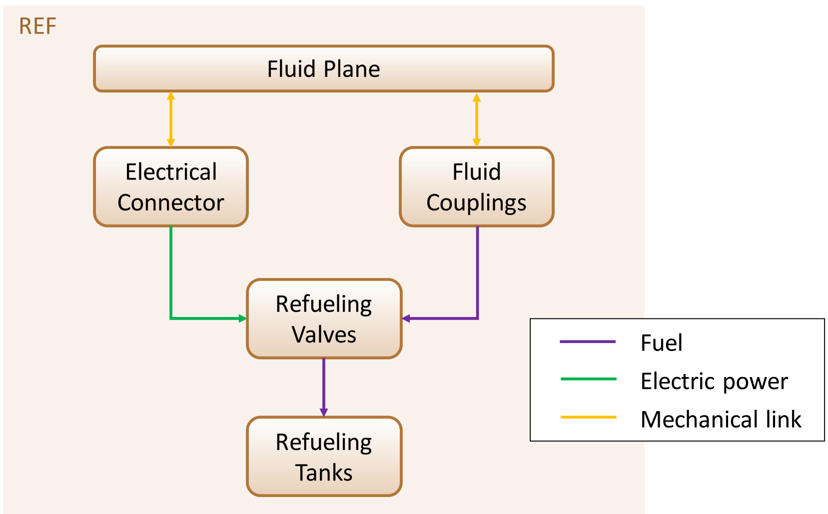


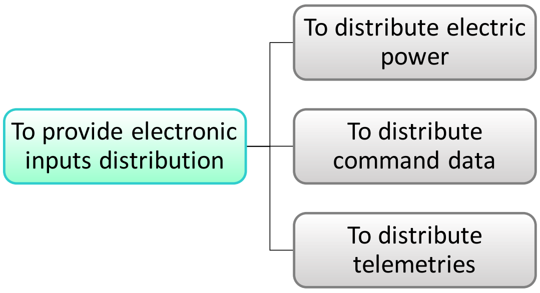

Figure 4.20: Functional Block Diagram - REF

### 4.2.9 Harness Subsystem

As indicated in the Functional Tree in Figure 4.21, the HARN subsystem is responsible for the distribution of telemetries and commands, as well as of electric power throughout the spacecraft. In particular, as shown in the Functions/Products Matrix of Figure 4.21 , components that shall perform these tasks are:

- Data Bus: it covers all hardware components, software and communication protocols that allow data to be transferred between units;

- Electric Power Harness: it consists of the assembly of electrical cables and wires which transmit electrical power throughout the vehicle.




| | | HARN | |
|---|---|---|---|
| | | Data Bus | Electric Power Harness |
| Functions | To distribute electric power | | X |
| | To distribute command data | X | |
| | To distribute telemetries | X | |

Figure 4.21: Functional Tree (left) and Functions/Products Matrix (right) - HARN

### 4.2.10 Functional Architecture at Subsystem Level

To complete the functional description of the ICV at Subsystem Level, we need to determine how all the components identified in previous paragraph are interrelated.

The Connection Matrix in Figure 4.22 indicates which elements are interfaced, and provides the groundwork for the development of the Functional Block Diagram in Figure 4.23.

As described in paragraph 4.2.1 the PPU interfaces with the Thruster Units, the PCDU and the RIU. It also shall have heat removed by heat pipes and shall be thermally monitored through Temperature Sensors and protected by Radiation Shields. In fact, Radiation Shields act as a barrier to protect electrical devices and cables from radiation damages. For this reason, besides shielding the PPU, they also interface with Batteries, the PCDU, the Electrical Heaters and all other electrical devices, and with the Data Bus and the Electric Power Harness.

Temperature Sensors and Electrical Heaters interfaces with all the elements that need accurate thermal monitoring and control, for example, the Fuel Tanks. In the Fuel Tanks Xenon temperature has stringent requirements that shall be satisfied. Furthermore, propulsion lines and tanks must be protected from freezing to correctly operate. This occurs also to the Docking I/F and the Refueling I/F. As explained in paragraph 4.2.6, sensors provides temperature measurements to TCS

| | PPU | Thruster Units | Fuel Tanks | Feeding System | Orbit Sensors | Attitude Sensors | AOCS Actuators | AOCS OBC | Solar Arrays | Batteries | PCDU | Heat Pipes | MLI Blankets | Radiators | Electrical Heaters | TCS OBC | Temperature Sensors | Radiation Shields | MDPS Panels | Primary Structure | Secondary Structure | Docking I/F | Grasping I/F | Fluid Plane | Fluid Couplings | Electrical Connector | Refueling Valves | Refueling Tank | Commands Decoder | OBC | Data Storage Unit | RIU | Antennas | Receiver | Transmitter | Auto-tracking equipment | Data Bus | Electric Power Harness |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PPU | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Thruster Units | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Fuel Tanks | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Feeding System | | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Orbit Sensors | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Attitude Sensors | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| AOCS Actuators | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| AOCS OBC | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Solar Arrays | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Batteries | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| PCDU | X | | | | X | X | X | | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Heat Pipes | X | | | | X | X | | | | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| MLI Blankets | | | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Radiators | | | | | | | | | | | | X | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Electrical Heaters | | X | X | X | X | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| TCS OBC | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Temperature Sensors | X | X | X | X | X | X | X | | X | X | X | | | | X | | | | | | | | | | | | | | | | | | | | | | | |
| Radiation Shields | X | | | | | | | | | X | X | | | | X | X | | | | | | | | | | | | | | | | | | | | | | |
| MDPS Panels | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Primary Structure | | X | X | | | | X | | | | | | X | | | | | | X | | | | | | | | | | | | | | | | | | | |
| Secondary Structure | X | | | X | X | X | | | X | X | X | X | X | X | X | | X | X | | | | | | | | | | | | | | | | | | | | |
| Docking I/F | | | | | | | | | | | | | X | | X | | X | | | X | | | | | | | | | | | | | | | | | | |
| Grasping I/F | | | | | | | | | | | | | X | | X | | X | | | X | | | | | | | | | | | | | | | | | | |
| Fluid Plane | | | | | | | | | | | | | | | | | | | | | X | | | | | | | | | | | | | | | | | |
| Fluid Couplings | | | | | | | | | | | | | | | | | | | | | | | | X | | | | | | | | | | | | | | |
| Electrical Connector | | | | | | | | | | | | | | | | | | | | | | | | X | | | | | | | | | | | | | | |
| Refueling Valves | | | | | | | | | | | | | | | | | | | | | X | | | | X | X | | | | | | | | | | | | |
| Refueling Tank | | | X | | | | | | | | | | | | | | | | | | | | | | | | X | | | | | | | | | | | |
| Commands Decoder | | | | | | | | | | | X | X | | | X | | X | X | | | X | | | | | | | | | | | | | | | | | |
| OBC | | | | | | | | X | | | X | X | | | X | X | X | X | | | X | | | | | | | | X | | | | | | | | | |
| Data Storage Unit | | | | | | | | | | | X | X | | | X | | X | X | | | X | | | | | | | | | X | | | | | | | | |
| RIU | X | | | X | X | X | X | X | | | X | X | | | X | X | X | X | | | X | | | | | | X | | | X | X | | | | | | | |
| Antennas | | | | | | | | | | | X | | | | | | X | | | | X | | | | | | | | | | | | | | | | | |
| Receiver | | | | | | | | | | | X | X | | | X | | X | X | | | X | | | | | | | | X | | | | X | | | | | |
| Transmitter | | | | | | | | | | | X | X | | | X | | X | X | | | X | | | | | | | | | X | | | X | | | | | |
| Auto-tracking equipment | | | | | | | | X | | | X | X | | | X | | X | X | | | X | | | | | | | | | | | | | | | | | |
| Data Bus | X | | | X | X | X | X | X | | | X | | | | | X | X | X | | | X | | | | | | | | X | X | X | X | | X | X | X | | |
| Electric Power Harness | X | X | | | X | X | X | X | X | X | X | | | | X | X | X | X | | | X | | | | | | | | X | X | X | X | X | X | X | X | X | |

Figure 4.22: ICV global Connection Matrix

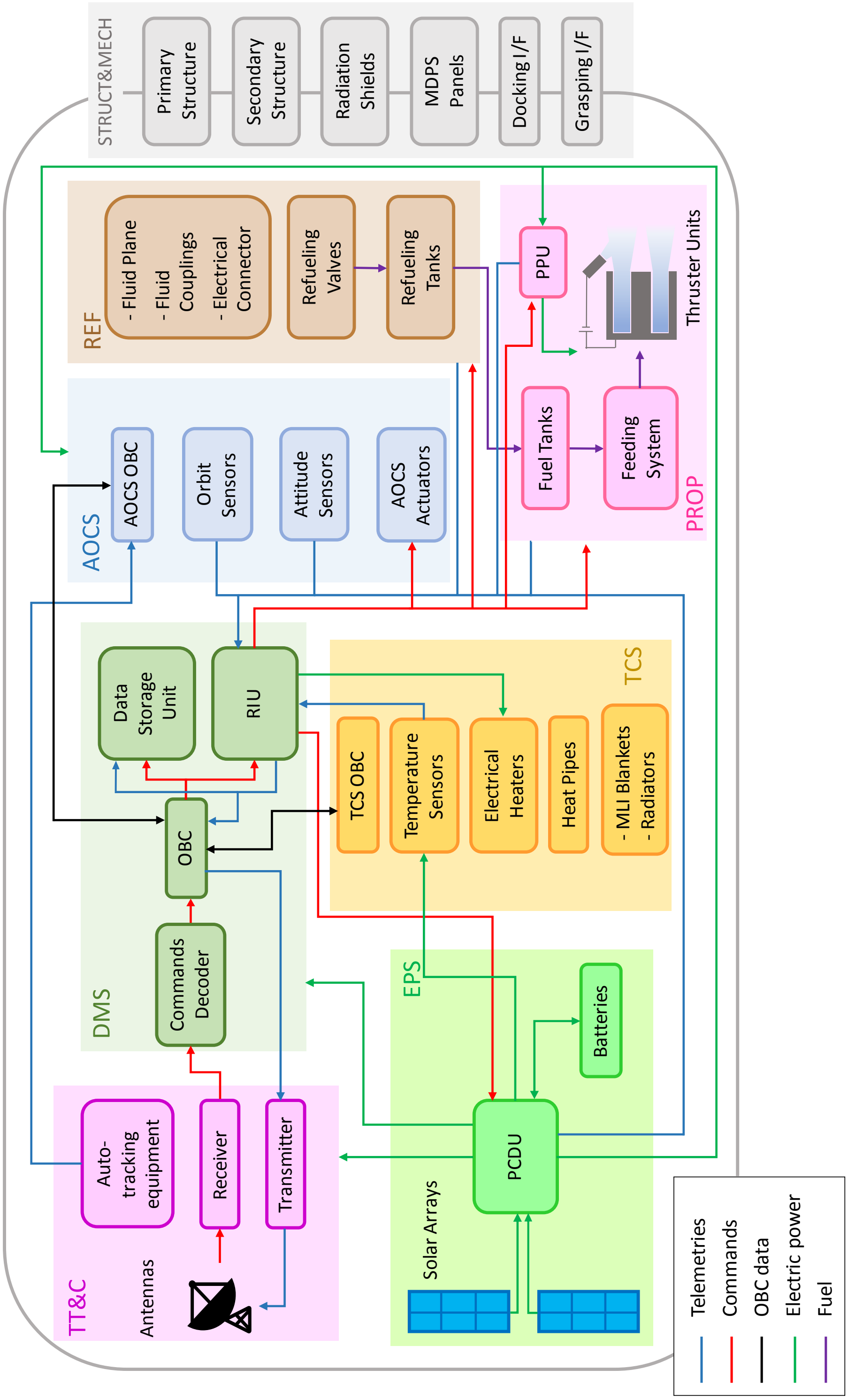



Figure 4.23: Global Functional Block Diagram

OBC, that consequently command Electrical Heaters to adjust the temperature, supplying or dissipating heat.

Thermal connections have been also identified for Orbit and Attitude Sensors. AOCS sensors on board spacecraft commonly are sun sensors, star sensors and magnetometers. The first two are optical devices, thus they produce heat that shall be transferred away through Heat Pipes. On the contrary, magnetometers need to be heated, often up to 100°C, to be operated. Heat Pipes interface with batteries and electronic components, since they dissipate heat and need rejection of this heat for their optimum and reliable operations. Between them, the PCDU is usually one of the most dissipative unit.

The PCDU is connected to all electrical devices, to which it provides electric power. Some kinds of AOCS actuators also needs electric supply, like control moment gyros, reaction wheels and momentum wheels, since they are all controlled by motors. Batteries and solar arrays are connected with the PCDU as explained in paragraph 4.2.3.

MLI Blankets interface with the Fuel Tanks and the Feeding system, since they are typically used to isolate propellant tanks and lines. They also cover great part of the Primary Structure. The Primary Structure mechanically interface with the major equipment, such as Thruster Units, the Fuel Tanks and the AOCS Actuators. Other components are mounted on the Secondary Structure, as well as the appendages like solar arrays and antennas.

The AOCS OBC and the TCS OBC interface with the OBC, because they are considered integrated in the OBC, which represent the central processor of the ICV.

### 4.2.11 Physical Block Diagram

Besides the Functional Block Diagram of Figure 4.23, a second block diagram has been developed. In this case the functional connections are indicated within a configuration more similar to a physical arrangement. In fact, there are components that present functional differences but that physically correspond. On the contrary, there are elements that coincide from a functional point of view but are physically separated. The Physical Block Diagram in Figure 4.24 takes into account these considerations and provides an alternative but also complementary point of view on the functional architecture. Among the main differences from the previous block diagram, it can be noticed that AOCS actuators have been distinguished in Attitude Control Actuators and in Orbital Control Actuators. Attitude Control Actuators include reaction wheels, momentum wheels and control moment

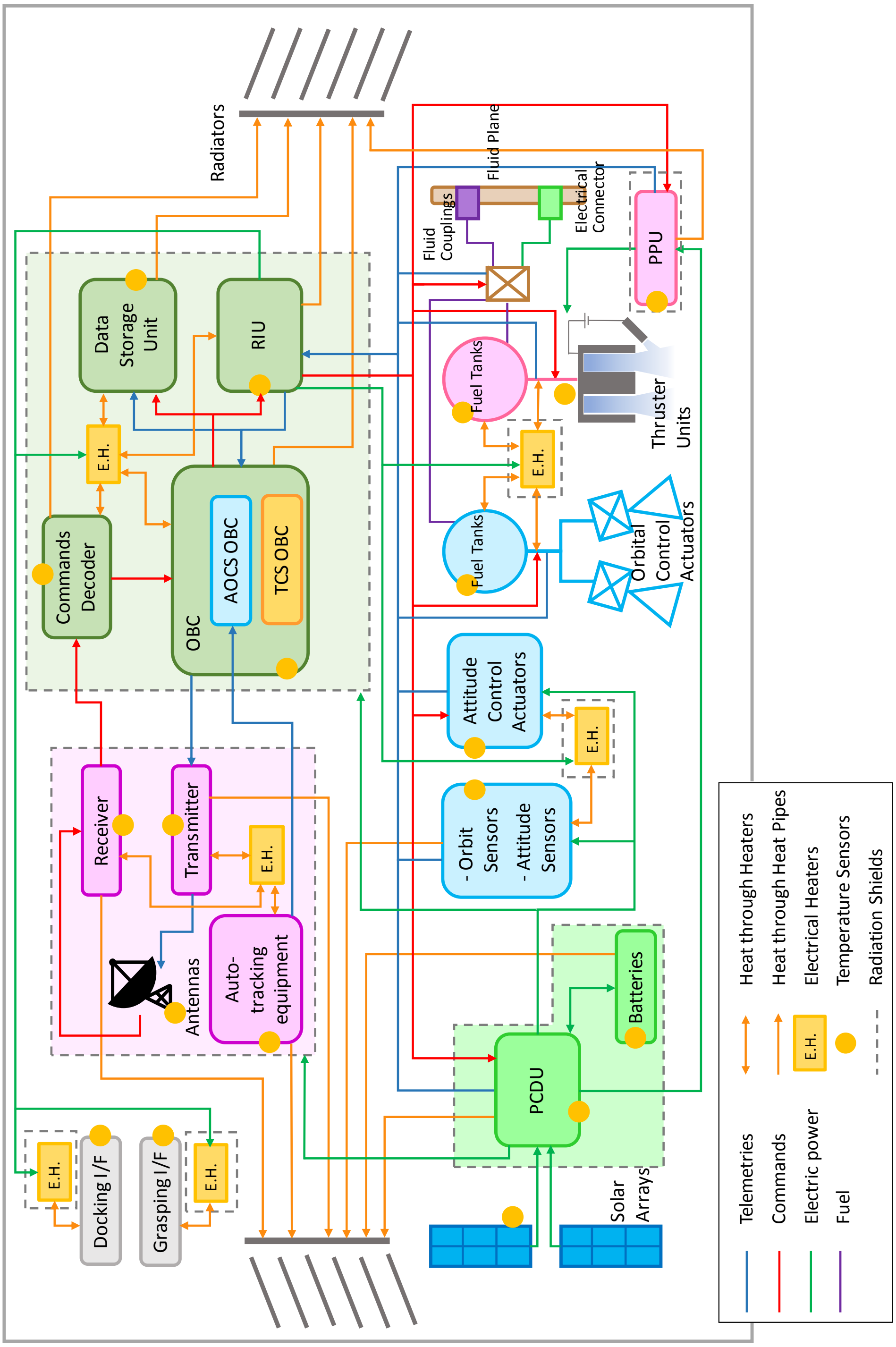



Figure 4.24: Physical Block Diagram

gyros, while Orbital Control Actuators are chemical thrusters and are more properly located in the PROP subsystem from a physical point of view. These latter are used for the rendezvous and mating operation with other on-orbit systems as will be described in the Modes of Operations analysis in Chapter 5. They are also used for the desaturation of the wheels when wheels become incapable of providing more torque on their axes.

Temperature Sensors and Electrical Heaters are not illustrated in a separated subsystem as they are in the Functional Block Diagram. They are instead shown near the elements that shall be monitored and the heat connections are also indicated. One-way arrows represent heat that is transferred through Heat Pipes from component to Radiators. Two-way arrows indicates the heat that is exchanged between Electrical Heaters and components.

The TCS OBC and the AOCS OBC have different functions from the OBC, and, from a functional perspective, they are included in two different subsystems. Nevertheless, they are integrated in the central processor and are positioned in the DMS subsystem. Similarly, Fuel Tanks and Refueling Tanks coincide in the physical arrangement, but they are associated with two different functions of the developed Functional Tree.

# Chapter 5

# Concept of Operations

The Concept of Operations (ConOps) describes how the system will be operated during all various life-cycle phases to meet stakeholder expectations. The ConOps is an important design tool able to capture both system requirements and architecture features, including some of which might be overlooked otherwise. Because it represents a crucial point in the mission definition and system design, the ConOps analysis must be carried on since the early design phases. Moreover, it serves as basis for subsequent definition documents such as the operations plan, Launch and Early Orbit Phase (LEOP) plan, and operations handbook. It also provides the foundation for the long-range operational planning activities, e.g. operational facilities, staffing, and network scheduling.
As introduced before, the ConOps analysis involves all the operations from the launch up to the disposal of the system at the End-of-Life (EOL). In particular, the mission definition is provided by the description of the major mission phases, the operational scenarios through the system traffic plan, the Design Reference Mission (DRM), which shows graphically the step-by-step sequence of the mission, each step corresponding to a different phase, the concerned orbit and the exploited infrastructures, It is an essential overview from launch to end of the mission, and the Phases Block Diagram (PBD) which shows conceptually the step-by-step sequence of the mission phases, illustrating the operational cycle of the ICV mission, main feature of this tool is to be able to emphasize the repetition of a phases cycle that is always the same as itself during the mission course. Analogously to the Function Analysis, the ConOps analysis is an iterative and recursive process, which shall be repeated until the desired level of detail is reached. In each stage of the design process, it is possible to define different type of requirements with different influences over the design [12, 14].

## 5.1 Scenarios Identification

Once the building blocks involved in the mission have been defined during the Functional Analysis, several scenarios and architectures have been identified and then compared among each other in order to select the optimal solution compliant with the mission statement, the stakeholders' needs and the requirements. Each of the identified scenarios has peculiar influences not only on the ICV functions and mission phases, but also on the features of the other orbital elements the ICV shall interface with. The ICV mission scenarios identified are the following:

**1a)** The ICV reaches the LOP-G and docks the Cargo Module, which is already attached at one of the LOP-G docking ports. After that, the ICV is grabbed by the LOP-G robotic arm in order to be moved to the LOP-G refueling port whereas the Cargo Module is prepared for the transfer. Once the refueling operation are completed, the robotic arm moves the ICV back to the Cargo Module, ready for the departure operations.

**1b)** In the second scenario, first the ICV docks the Cargo Module and then it autonomously reaches the refueling port without the support of the robotic arm. Once the ICV is refueled, it reaches again the Cargo Module, which has been prepared for the transfer in the meantime, and it is ready to start the mission towards the MOS.

**1c)** The ICV refueling is performed though a refueling arm while the ICV is docked to the Cargo Module. Once refueling is completed, cargo handling is performed. Then the ICV is ready for departure procedures.

**1d)** In the last case, the ICV is refueled at the LOP-G using a refueling tool which passes through the Cargo Module. Once the refueling of the ICV is completed and the Cargo Module has been prepared, the ICV can leave the LOP-G towards the MOS.

Among these scenarios, a preliminary trade-off analysis has been performed in order to point out the most suitable solutions according to the following Figures of Merits (FoM):

- *Docking operations*: number of docking maneuvers required in the scenario. Increased number of docking maneuvers involves the rise in risk of collision with the station;
- *Berthing operations*: number of relocations through berthing maneuvers. Decreased risk of collision with the station and reduction in fuel consumption;

- *Proximity maneuvers*: number of relocations without robotic arm. Increased risk of collision with the station and rise in fuel consumption;
- *Use of refueling arm*: refueling through refueling arm. Inadequate knowledge about this kind of technology and absence of past applications;
- *Refueling through Cargo Module*: refueling through Cargo Module. Greater knowledge about this kind of technology and presence of past similar applications.

The Figures of merits presented above, since they all strongly influence the scenario, have all the same weight equal to 1. Each of these FOMs may be present or not present in the scenario, therefore, we have chosen to attribute score 1 in the event that the FOM is present and score 0 if it is absent. The only exception is represented by *Docking operations*, which is evaluated with a numbering directly proportional to the count of docking maneuvers present in a single end-to-end mission and normalized to 1 (maximum number of docking operations is 4 in scenario 1b, all the others scenarios present only 2 docking maneuvers, so the final value for each scenario is obtained by dividing the number of docking maneuvers by 4).

*Berthing operations* and *Refueling through Cargo Module* are Figures of merit whose presence is positively evaluated as they increase the reliability degree of the mission. On the other hand, *Proximity maneuvers*, *Use of refueling arm* and *Docking operations* are Figures of merit whose presence is negatively evaluated as they decrease the reliability degree of the mission.

The results of the analysis are shown in Table 5.1.

| | 1a | 1b | 1c | 1d |
|---|---|---|---|---|
| Docking operations | 0.5 | 1 | 0.5 | 0.5 |
| Berthing operations | 1 | 0 | 0 | 0 |
| Proximity maneuvers | 0 | 1 | 0 | 0 |
| Use of refueling arm | 0 | 0 | 1 | 0 |
| Refueling through Cargo Module | 0 | 0 | 0 | 1 |
| Total score | -0.5+1= **0.5** | -1-1= **-2** | -0.5-1= **-1.5** | -0.5+1= **0.5** |

Table 5.1: Scenarios identification

As shown in Table 5.1, scenarios 1a and 1d provide solutions more reliable rather than scenarios 1b and 1c. Hence, these selected scenarios will be analyzed in detail in the next Section whereas, from a functional point of view, the corresponding platforms have been presented in Chapter 4.

## 5.2 ICV Basic Configurations

ICV is exploited for cargo transportation mission, so, the spacecraft can assume two main configurations based on the Cargo Module. A conceptual and basic system design has been developed. In this section only the system-level configuration is considered, all the configurations at subsystem level are referred to the subsequent Section 5.5 concerning the Modes of Operations.

- *Not loaded*, in this configurations the Cargo Module is not attached to ICV and the docking interface is able to dock directly with the LOP-G docking ports (e.g. refueling docking port). The Figure 5.1 shows the placement of the solar arrays, the position of the main HETs and the position of the docking interface.

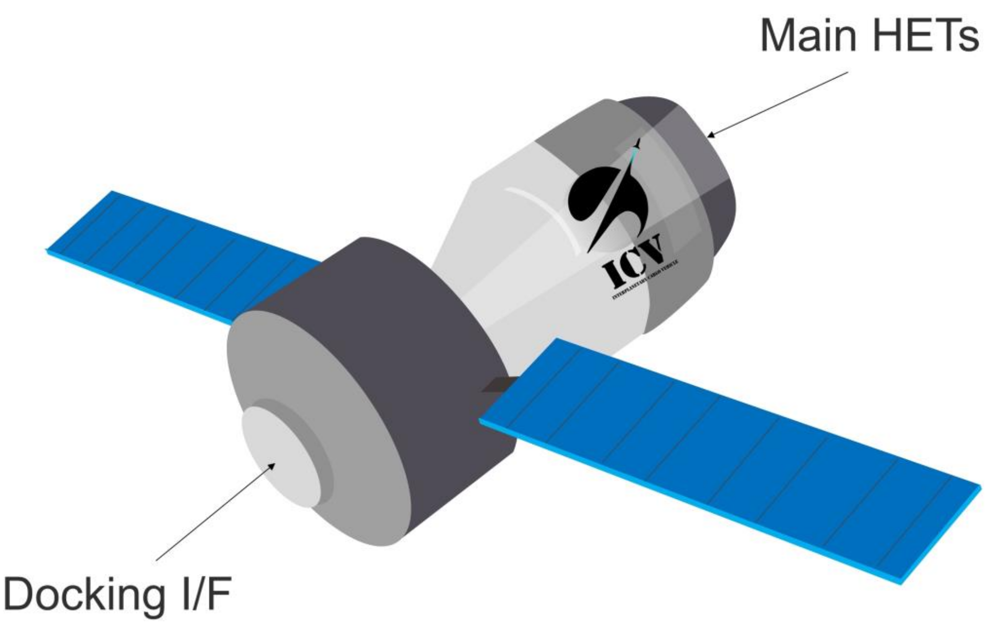



Figure 5.1: Not loaded configuration

- *Loaded*, in this configurations the Cargo Module is attached to ICV. The only docking interface able to dock directly with the LOP-G docking port is the Cargo Module one. The Figure 5.2 shows the placement of the Cargo Module and the positions of the relative docking interfaces.

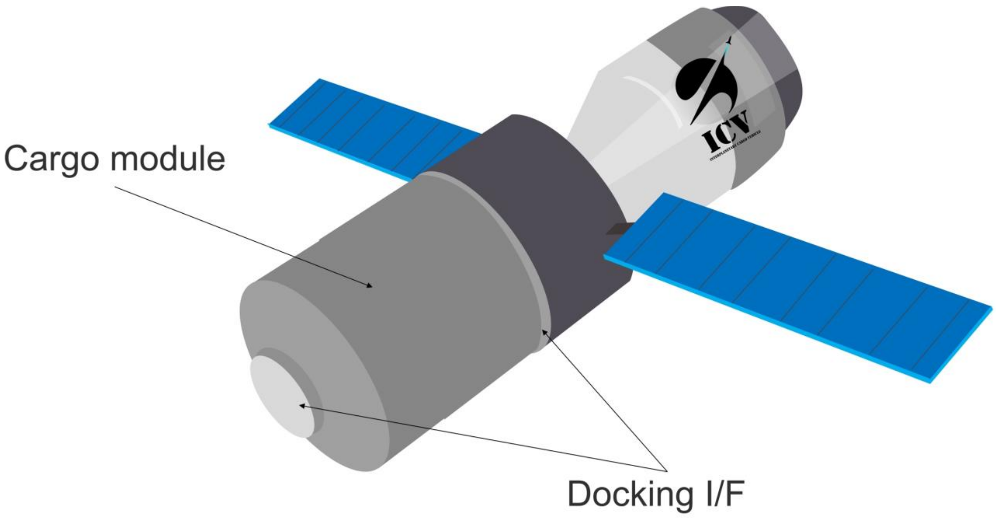



Figure 5.2: Loaded configuration

## 5.3 Mission Phases

The first ConOps step consists of identifying the high-level mission phases, shared among both selected scenarios, and characterized them though their peculiar features and properties. Then, the two scenarios are graphically represented in their preliminary DRM and corresponding PBD which allow to obtain a more clear and intuitive idea of the mission [17].

### 5.3.1 Preliminary Mission Phases Identification

As anticipated before, each scenario can be split in several phases, each one characterized by a well precise state of the system defined by the external environment (natural and induced environments, e.g. radiation, electromagnetic, heat, vibration and contamination environment) within which the system operates. The transition between one state of the system to the next one corresponds also to the transition between two phases. Hence, each mission phase is therefore characterized by a specific orbit and environment, in terms of loads, available resources, external temperatures and pressure, radiation. Accordingly to the considerations made above, the whole mission has been split into fifteen phases. Below we have characterized them from an operational point of view.

1. *Launch:*
   all the operations required to put, through a launcher, the ICV into LEO.
2. *Early operations:*
   all the operations needed to check the subsystems.
3. *EOR to LOP-G:*
   the electric orbit raising from LEO to LOP-G orbit.
4. *Rendezvous and mating with LOP-G from Earth orbit:*
   all the operations requested in the LOP-G vicinity to attach ICV with LOP-G from Earth orbit.
5. *Logistics, checking and maintenance:*
   all the operations requested to guarantee the proper operation of the ICV and the maintenance operations of the whole system.
6. *Cargo handling at LOP-G:*
   all the operations needed to deliver and retrieve the cargo module according to the mission requests.
7. *Refueling:*
   all the operations requested to accomplish the ICV refueling.
8. *Unmating from LOP-G:*
   all the operations needed to detach ICV from LOP-G.
9. *LOP-G – MOS EOR:*
   the electric orbit raising requested to reach the MOS orbit from LOP-G orbit.
10. *Rendezvous and mating with MOS:*
    all the operations requested in the MOS vicinity to attach ICV with MOS from deep space.
11. *Logistics and checking:*
    all the operations requested to guarantee the proper operation of the ICV.
12. *Cargo handling at MOS:*
    all the operations needed to deliver and retrieve the cargo module according to the mission requests.

13. *Unmating from MOS:*
    all the operations needed to detach ICV from MOS.

14. *MOS – LOP-G EOR:*
    the electric orbit raising requested to reach the LOP-G orbit from MOS orbit.

15. *Rendezvous and mating with LOP-G from deep space:*
    all the operations requested in the LOP-G vicinity to attach ICV with LOP-G from Earth orbit.

At this point of the analysis, the phases relating to the disposal do not yet appear since they are introduced only afterwards following the refinement related to each scenario.

Table 5.2 and Table 5.3 provide the main features of each phase in terms of starting and ending events, initial orbit, final orbit, phase description, environment and Cargo Module configuration. In addition, a color coding has been used to facilitate understanding of the surrounding environment. In detail, each color corresponds to a faced environment: green for Earth orbit/cislunar space, grey for Lunar orbit, light blue for Deep space and Orange for Mars orbit.

| No. | Phase | Start | End | Initial orbit | Final orbit | Description | Environment | Cargo module configuration |
|---|---|---|---|---|---|---|---|---|
| 1. | Launch | Lift-off | Separation from launcher | Ground | LEO | Operations required to put into LEO the ICV through a launcher | Payload envelope | Not loaded |
| 2. | Early operations | Separation from launcher | ICV ready for EOR | LEO | LEO | Operations needed to check the ICV subsystems | Earth orbit | Not loaded |
| 3. | EOR to LOP-G | ICV ready for EOR | ICV arrival in the proximity of LOP-G | LEO | LOP-G orbit | LEO to LOP-G EOR | Cis-lunar | Not loaded |
| 4. | Rendezvous and mating with LOP-G from Earth orbit | ICV arrival in the vicinity of LOP-G | ICV attached to LOP-G | LOP-G orbit | LOP-G orbit | Operations requested in the LOP-G vicinity to attach ICV with LOP-G from Earth orbit | Lunar orbit | Not loaded |
| 5. | Logistics, checking and maintenance | ICV attached to LOP-G | ICV ready for cargo handling | LOP-G orbit | LOP-G orbit | Operations requested to guarantee the proper operation of the ICV and the maintenance operations of the whole system | Lunar orbit | Not loaded |
| 6. | Cargo handling at LOP-G | ICV ready for cargo handling | Cargo module managed on ICV | LOP-G orbit | LOP-G orbit | Operations needed to deliver and retrieve the cargo module according to the mission requests | Lunar orbit | Loaded |
| 7. | Refueling | Cargo module managed on ICV | ICV refueled and ready for detachment | LOP-G orbit | LOP-G orbit | Operations requested to accomplish the ICV refueling | Lunar orbit | Loaded |
| 8. | Unmating from LOP-G | ICV refueled and ready for detachment | ICV detached from LOP-G | LOP-G orbit | LOP-G orbit | Operations needed to detach ICV from LOP-G | Lunar orbit | Loaded |
| 9. | LOP-G – MOS EOR | ICV detached from LOP-G | ICV arrival in the vicinity of MOS | LOP-G orbit | MOS orbit | Electric orbit raising requested to reach the MOS orbit | Deep space | Loaded |

Table 5.2: Table of phases (first part)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 10. | Rendezvous and mating with MOS | ICV arrival in the vicinity of MOS | ICV attached to MOS | MOS orbit | MOS orbit | Operations requested in the MOS vicinity to attach ICV with MOS | Mars orbit | Loaded |
| 11. | Logistics and checking | ICV attached to MOS | ICV ready for cargo handling | MOS orbit | MOS orbit | Operations requested to guarantee the proper operation of the ICV | Mars orbit | Loaded |
| 12. | Cargo handling at MOS | ICV ready for cargo handling | Cargo module managed and ICV ready for detachment | MOS orbit | MOS orbit | Operations needed to deliver and retrieve the cargo module according to the mission requests | Mars orbit | Loaded |
| 13. | Unmating from MOS | Cargo module managed and ICV ready for detachment | ICV detached from MOS | MOS orbit | MOS orbit | Operations needed to detach ICV from MOS | Mars orbit | Loaded |
| 14. | MOS – LOP-G EOR | ICV detached from MOS | ICV arrival in the vicinity of LOP-G | MOS orbit | LOP-G orbit | Electric orbit raising requested to reach the LOP-G orbit | Deep space | Loaded |
| 15. | Rendezvous and mating with LOP-G from deep space | ICV arrival in the vicinity of LOP-G | ICV attached to LOP-G | LOP-G orbit | LOP-G orbit | Operations requested in the LOP-G vicinity to attach ICV with LOP-G from deep space | Lunar orbit | Loaded |

Table 5.3: Table of phases (second part)

### 5.3.2 Environmental Requirements

New requirements arise from the analysis of the mission phases: they are the *Environmental Requirements*. As described at the beginning of this section, each mission phase is characterized by a specific environment, both natural and induced. Environmental Requirements, thus, focuses on natural and induced conditions that constrain the ICV's features. In Table 5.4 some examples are indicated for two different mission phases.

| | |
|---|---|
| **Launch** | *The ICV shall withstand launch environment during launch;* |
| | *The ICV shall be able to sustain launch loads during launch;* |
| | *The ICV shall be able to sustain launch vibration during launch;* |
| | *The ICV shall limit heat leak/gain to/from natural environment during launch;* |
| | *The ICV shall withstand TBD temperature range during launch;* |
| | *ICV shall be able to sustain separation shock during launch.* |
| **EOR to LOP-G** | *The ICV shall withstand EOR environment during EOR from LEO to LOP-G;* |
| | *ICV shall be able to sustain operational loads during EOR from LEO to LOP-G;* |
| | *The ICV shall limit heat leak/gain to/from natural environment during EOR from LEO to LOP-G;* |
| | *The ICV shall be able to operate within TBD temperature range during EOR from LEO to LOP-G;* |
| | *The ICV shall be able to sustain a TBD radiation dose during EOR from LEO to LOP-G;* |

Table 5.4: Examples of *Environmental Requirements* for the *Launch* phase and the *EOR to LOP-G* phase

Requirements driving components sizing can be established if environmental requirements from all phases are taken into account. For example, considering radiation dose from the various environments, the total radiative dose that radiation shields have to counteract can be fixed. This total dose would drive the radiation shields sizing.

### 5.3.3 Preliminary Design Reference Mission (DRM)

Like any other space mission, the ICV mission begins with the launch. Once the desired Earth orbit is reached, ICV is released by the launcher and the preliminary operations begin. These kind of operations continue until the proper functioning of the spacecraft has been tested. Once the Ground Station clearance is obtained, the first electric orbit rising is performed in order to reach the LOP-G orbit. At the end of the orbital transfer, when ICV reaches 30 km from the station, the rendezvous and mating phase is accomplished. At this time ICV is docked to LOP-G. Subsequently, the maintenance, control, logistics, cargo handling and refueling phases are carried out in sequence. After have accomplished all these operations, the spacecraft, with its cargo module, separates from the station and starts the second electric orbit rising with the aim of reaching the MOS orbit. At the end of the deep space transfer, when ICV reaches 30 km from the MOS, the rendezvous and mating phase is performed. In Martian orbit, while docked to MOS, the control, logistics and cargo handling phases are carried out in sequence. After have accomplished all these operations, the spacecraft separates from the station and starts the third electric orbit rising in order to return in the LOP-G orbit. Once the station orbit is reached, the rendezvous and mating from deep phase is accomplished and the mission cycle can proceed. In Figure 5.3 is shown the related DRM.

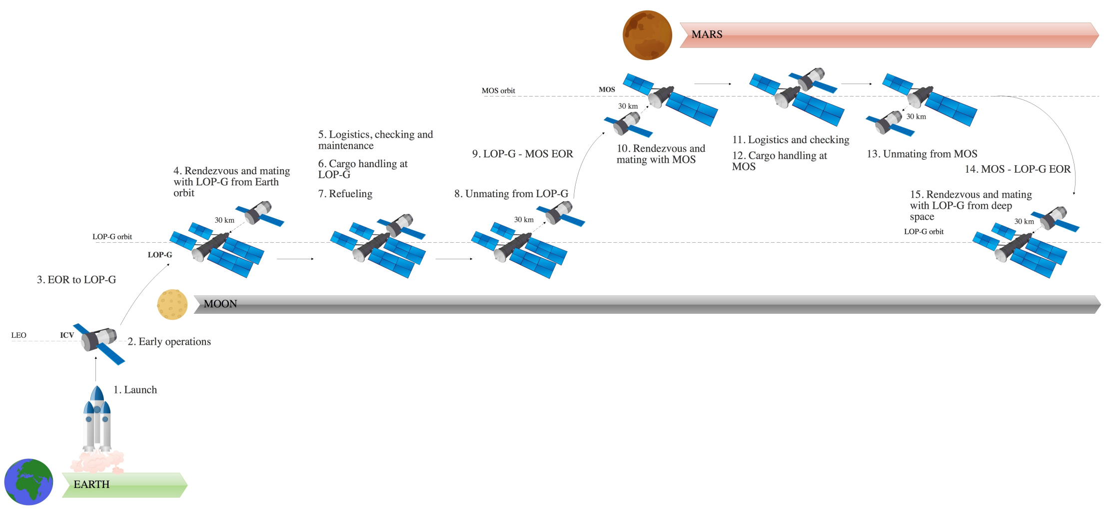



Figure 5.3: Design Reference Mission

### 5.3.4 Preliminary Phases Block Diagram (PBD)

The Phases Block Diagram shows the different parts of the mission. The first part of the diagram represents all the phases necessary to start the effective operating cycle and it is constituted by phases 1,2,3 and 4. The second part of the diagram represents all the phases necessary to perform the effective operating cycle of the transportation mission, it is constituted by phases 5 to 15. These ones are repeated identically until the end of the mission.
A color coding has been used to facilitate understanding of the blocks. In detail, each color corresponds to a reached orbit: green for Earth orbit/cislunar space, grey for Lunar orbit, light blue for Deep space and Orange for Mars orbit. In addition, a stream of arrows guides the succession of the different phases. In Figure 5.4 is shown the relative PBD.

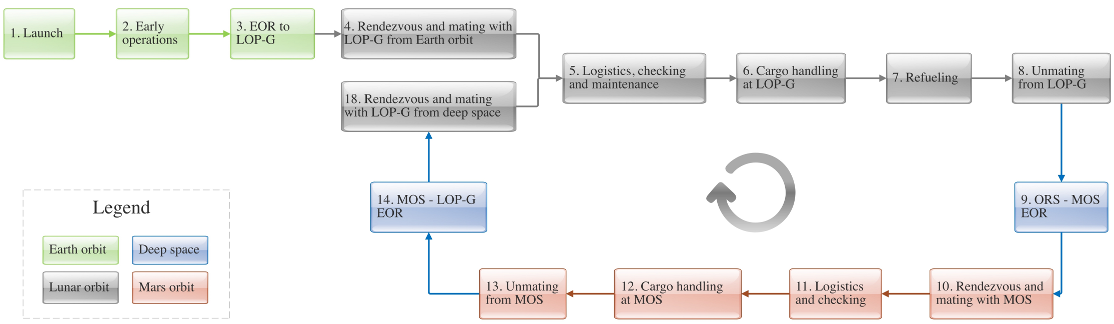



Figure 5.4: Phases Block Diagram

## 5.4 Mission Phases Refinement

The second ConOps step consists of identifying the lower-level mission phases, specified for each selected scenarios, and characterized them though their peculiar features and properties. Then, the two scenarios are graphically represented to their complete DRM and corresponding PBD which allow to obtain a more clear and intuitive idea of the whole mission.

### 5.4.1 Mission Phases Specification for Scenario 1a

In this section, the phases identified previously in Section 5.3.1 have been studied in detail for Scenario 1a. In particular, only the phases with significant differences from the previous version are reported and specified. During the the mission study, we have chosen to always perform docking maneuvers as mating operations because of MOS is not equipped with a robotic arm capable of performing berthing operations. Below, the phases characterization from operational point of view.

- *Launch*, *Early operations* and *EOR to LOP-G* are the same as the previous identified.

4 *Rendezvous and docking at LOP-G refueling docking port:*
all the operations required in LOP-G vicinity to dock ICV to LOP-G refueling docking port.

5 *Refueling:*
all the operations required to transfer fuel to ICV tank.

6 *Berthing and undocking (at LOP-G refueling docking port):*
all the operations required to attach ICV grasping mechanism to LOP-G robotic arm and to undock ICV from LOP-G refueling docking port.

7 *Relocation to Cargo module:*
mechanical displacement of the ICV, by means of LOP-G robotic arm, from LOP-G refueling docking port to Cargo module docking port.

8 *Docking and release (at Cargo module):*
all the operations required to dock ICV at Cargo module docking port and to detach ICV grasping mechanism from LOP-G robotic arm.

9 *Undocking from LOP-G:*
all the operations required to undock Cargo module from LOP-G.

- *LOP-G – MOS EOR*, *Rendezvous and docking with MOS*, *Checking and Cargo handling at MOS*, *Undocking from MOS* and *MOS – LOP-G EOR* are the same as the previous identified.

15 *Rendezvous and docking with LOP-G:*
all the operations required in the LOP-G vicinity to dock Cargo module to LOP-G docking port.

16 *Logistics, checking and maintenance:*
all the operations required to verify and guarantee the proper functioning of ICV.

17 *Berthing and undocking (at Cargo module):*
all the operations required to attach ICV grasping mechanism to LOP-G robotic arm and to undock ICV from Cargo module docking port.

18 *Relocation to LOP-G refueling docking port:*
mechanical displacement of ICV, by means of LOP-G robotic arm, from Cargo module docking port to LOP-G refueling docking port.

19 *Docking and release (at LOP-G refueling docking port):*
All the operations required to dock ICV to LOP-G refueling docking port and to detach ICV grasping mechanism from LOP-G robotic arm.

In addition, the disposal operations have been inserted at the end of the operational life of the ICV. The end-of-life is represented by the system switch-off once reached the assigned graveyard orbit. The phases that represent the *Disposal* are:

**D1** *Undocking from Cargo module:*
all the operations required to undock ICV from Cargo module.

**D2** *EOR to graveyard orbit and switch-off:*
the electric orbit raising from LOP-G orbit to graveyard orbit and system shutdown.

As explained in the Section 5.3.1, Table 5.5 and Table 5.6 provide the main features of each phase in terms of starting and ending events, initial orbit, final orbit, phase description, environment and Cargo Module configuration. In addition, a color coding has been used to facilitate understanding of the surrounding environment. In detail, each color corresponds to a faced environment: green for Earth orbit/cislunar space, grey for Lunar orbit, light blue for Deep space and Orange for Mars orbit.
In Table 5.5 and Table 5.6 all the phases are shown in order to provide an overview of the whole scenario.

| No. | Phase | Start | End | Initial orbit | Final orbit | Description | Environ ment | Cargo module configuration |
|---|---|---|---|---|---|---|---|---|
| 1. | Launch | Lift-off | Orbit insertion | Ground | LEO | Operations required to put into LEO the ICV through a launcher | Payload envelope | Not loaded |
| 2. | Early operations | Orbit insertion | ICV ready for EOR | LEO | LEO | Operations required to check the subsystems health status | Earth orbit | Not loaded |
| 3. | EOR to LOP-G | ICV ready for EOR | ICV arrival in LOP-G refueling docking port vicinity | LEO | LOP-G orbit | Electric orbit raising from LEO to LOP-G | Cis-lunar | Not loaded |
| 4. | Rendezvous and docking at the LOP-G refueling docking port | ICV arrival in LOP-G refueling docking port vicinity | ICV docked to LOP-G refueling docking port | LOP-G orbit | LOP-G orbit | Operations required in LOP-G vicinity to dock ICV to LOP-G refueling docking port | Lunar orbit | Not loaded |
| 5. | Refueling | ICV docked to LOP-G refueling docking port | ICV refueled | LOP-G orbit | LOP-G orbit | Operations required transfer fuel to ICV tank | Lunar orbit | Not loaded |
| 6. | Berthing and undocking (at LOP-G refueling docking port) | ICV refueled | ICV undocked from LOP-G refueling docking port | LOP-G orbit | LOP-G orbit | Operations required to attach ICV grasping mechanism to LOP-G robotic arm and to undock ICV from LOP-G refueling docking port | Lunar orbit | Not loaded |
| 7. | Relocation to Cargo module | ICV undocked from LOP-G refueling docking port | ICV ready for docking to Cargo module docking port | LOP-G orbit | LOP-G orbit | Mechanical displacement of the ICV, by means of LOP-G robotic arm, from LOP-G refueling docking port to Cargo module docking port | Lunar orbit | Not loaded |
| 8. | Docking and release (at Cargo module) | ICV ready for docking to Cargo module docking port | ICV released by LOP-G robotic arm | LOP-G orbit | LOP-G orbit | Operations required to dock ICV at Cargo module docking port and to detach ICV grasping mechanism from LOP-G robotic arm | Lunar orbit | Not loaded |
| 9. | Undocking from LOP-G | ICV released by LOP-G robotic arm | Cargo module undocked from ICV | LOP-G orbit | LOP-G orbit | Operations required to undock Cargo module from LOP-G | Lunar orbit | Loaded |
| 10. | LOP-G – MOS EOR | Cargo module undocked from LOP-G | ICV arrival in MOS vicinity | LOP-G orbit | MOS orbit | Electric orbit raising required to reach the MOS orbit | Deep space | Loaded |
| 11. | Rendezvous and docking with MOS | ICV arrival in MOS vicinity | Cargo module docked to MOS | MOS orbit | MOS orbit | Operations required in MOS vicinity to dock Cargo module with MOS | Mars orbit | Loaded |

Table 5.5: Table of phases **1a** (first part)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 12. | Checking and Cargo handling at MOS | Cargo module docked to MOS | Cargo module managed and ready for undocking | MOS orbit | MOS orbit | Operations required to verify the proper functioning of ICV and to deliver/ retrieve cargo assets | Mars orbit | Loaded |
| 13. | Undocking from MOS | Cargo module managed and ready for undocking | Cargo module undocked from MOS | MOS orbit | MOS orbit | Operations required to undock Cargo module from MOS | Mars orbit | Loaded |
| 14. | MOS – LOP-G EOR | Cargo module undocked from MOS | ICV arrival in LOP-G vicinity | MOS orbit | LOP-G orbit | Electric orbit raising required to reach the LOP-G orbit | Deep space | Loaded |
| 15. | Rendezvous and docking with LOP-G | ICV arrival in LOP-G vicinity | Cargo module docked to LOP-G | LOP-G orbit | LOP-G orbit | Operations required in LOP-G vicinity to dock Cargo module with LOP-G | Lunar orbit | Loaded |
| 16. | Logistics, checking and maintenance | Cargo module docked to LOP-G | ICV ready for refueling operations | LOP-G orbit | LOP-G orbit | Operations required to verify and guarantee the proper functioning of ICV | Lunar orbit | Loaded |
| 17. | Berthing and undocking (at Cargo module) | ICV ready for refueling operations | ICV undocked from Cargo module docking port | LOP-G orbit | LOP-G orbit | Operations required to attach ICV grasping mechanism to LOP-G robotic arm and to undock ICV from Cargo module docking port | Lunar orbit | Loaded |
| 18. | Relocation to LOP-G refueling docking port | ICV undocked from Cargo module docking port | ICV ready for docking to Cargo module docking port | LOP-G orbit | LOP-G orbit | Mechanical displacement of ICV, by means of LOP-G robotic arm, from Cargo module docking port to LOP-G refueling docking port | Lunar orbit | Not loaded |
| 19. | Docking and release (at LOP-G refueling docking port) | ICV ready for docking to Cargo module docking port | ICV released by LOP-G robotic arm | LOP-G orbit | LOP-G orbit | Operations required to dock ICV to LOP-G refueling docking port and to detach ICV grasping mechanism from LOP-G robotic arm | Lunar orbit | Not loaded |
| D1. | Undocking from Cargo module | ICV arrival in LOP-G vicinity | ICV undocked from Cargo module | LOP-G orbit | LOP-G orbit | Operations required to undock ICV from Cargo module | Lunar orbit | Not loaded |
| D2. | EOR to graveyard orbit and switch-off | ICV undocked from Cargo module | ICV completely switched off | LOP-G orbit | Graveyard orbit | Electric orbit raising from LOP-G orbit to graveyard orbit and system shutdown | Cis-lunar | Not loaded |

Table 5.6: Table of phases **1a** (second part)

### 5.4.2 Design Reference Mission - 1a

The extended launch phase (represented in Figure 5.5 by the Roman number "I") includes launch, early operations, EOR to LOP-G and rendezvous and docking at LOP-G phases previously described in Section 5.3.3. The only difference specified is the used docking port; in this scenario is required, only for the first contact with the station, to dock at the refueling docking port.

At this point, the extended operative phase (represented in Figure 5.5 by the Roman number "II") can begin. Subsequently, the refueling, berthing with LOP-G robotic arm and undocking from LOP-G refueling docking port, relocation to Cargo Module and docking and release from the robotic arm at the Cargo Module docking port phases are carried out in sequence. After have accomplished all these operations, the spacecraft, with its cargo module, separates from the station and starts the second electric orbit rising with the aim of reaching the MOS orbit.

All the phases between the EOR to MOS orbit and the EOR returning to LOP-G orbit are the same as the previously described in Section 5.3.3.

Once the lunar station orbit is reached, the rendezvous and docking from deep phase is accomplished at the LOP-G docking port. After the logistic, checking and maintenance phase, ICV have to return in the refueling configuration. In order to ensure the correct procedure, berthing with LOP-G robotic arm and undocking from Cargo Module docking port, relocation to LOP-G refueling docking port and docking and release from the robotic arm at the LOP-G refueling docking port phases are carried out in sequence. In such a way the mission cycle can proceed until disposal.

The extended disposal phase (represented in Figure 5.6 by the Roman number "III"), which includes undocking from Cargo Module, EOR to graveyard orbit and system switch-off, represents the ICV end-of-life and the irreversible mission conclusion.

In Figure 5.5 and Figure 5.6 is shown the related DRM.

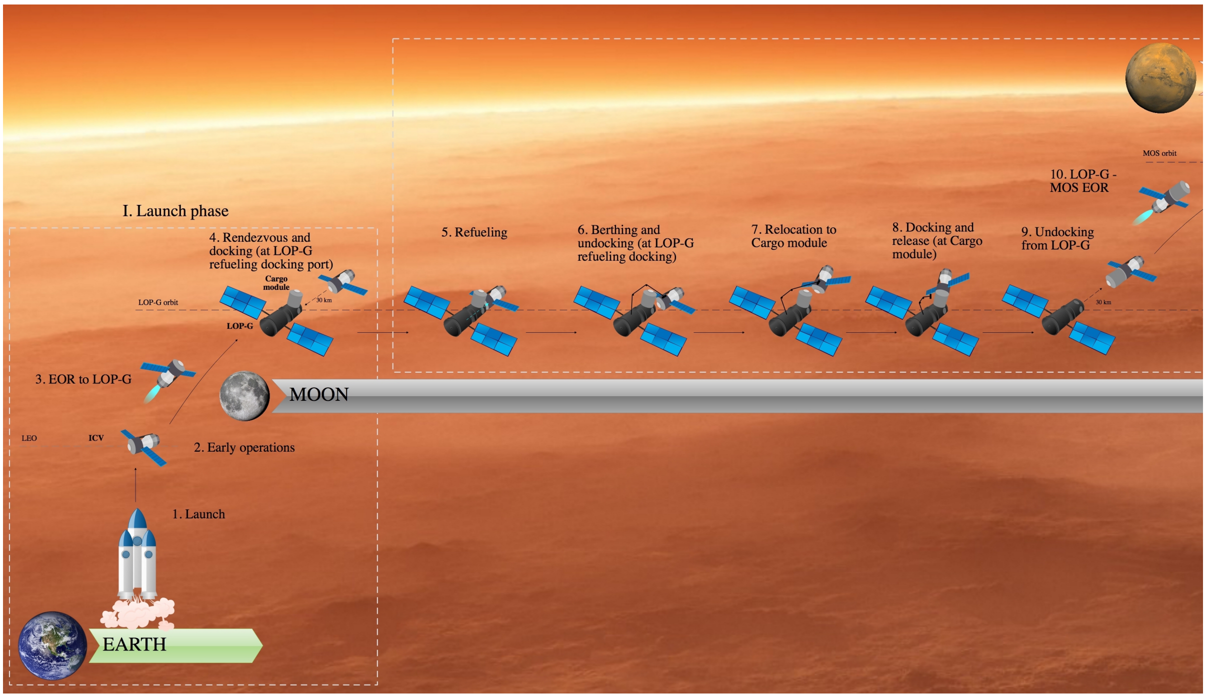



Figure 5.5: Design Reference Mission **1a** (first part)

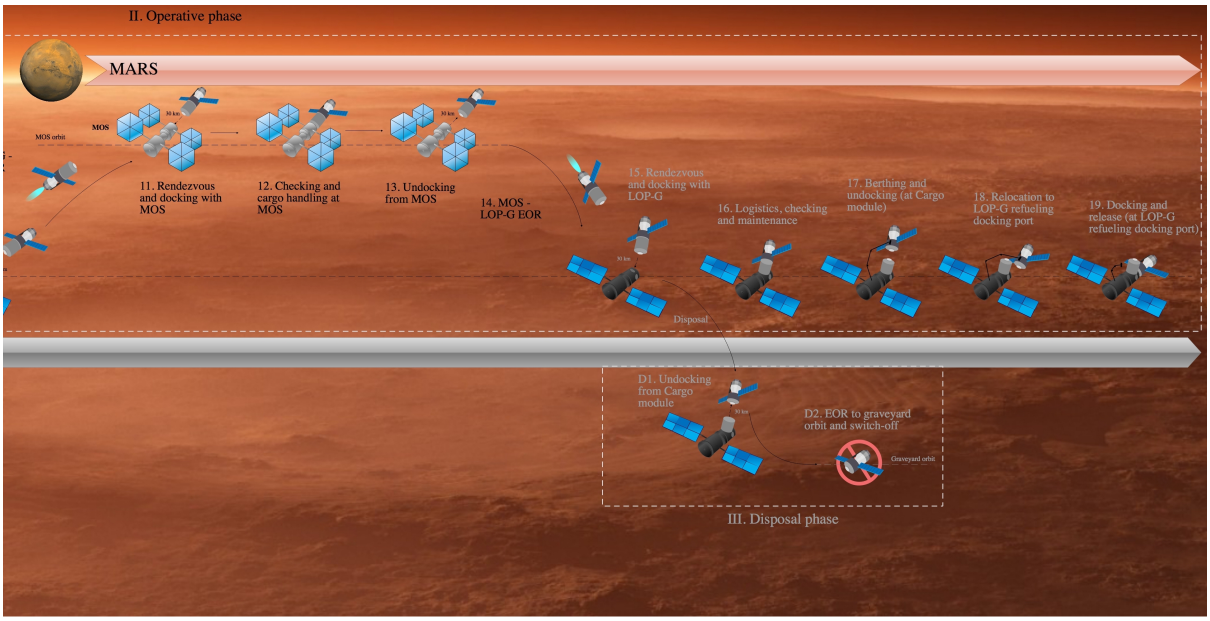



Figure 5.6: Design Reference Mission **1a** (second part)

### 5.4.3 Phases Block Diagram - 1a

The Phases Block Diagram shows the three main extended phases of the mission: launch, operative and disposal.

The first part of the diagram represents the launch phase, which is constituted by the phases necessary to start the effective operating cycle, that are phases 1,2,3 and 4.

The second part of the diagram represents the operational phase, which is constituted by the phases necessary to perform the effective operating cycle of the transportation mission, it is constituted by phases 5 to 19. These ones are repeated identically until the mission end.

The third part of the diagram represents the disposal phase, which is constituted by the phases necessary to perform the disposal and the end-of-life operations. It is constituted by phases D1 and D2.

As reported in the previous Section 5.3.4, a color coding has been used to facilitate understanding of the blocks. In detail, each color corresponds to a reached orbit: green for Earth orbit/cislunar space, grey for Lunar orbit, light blue for Deep space and Orange for Mars orbit. In addition, a stream of arrows guides the succession of the different phases. In Figure 5.7 is shown the relative PBD.

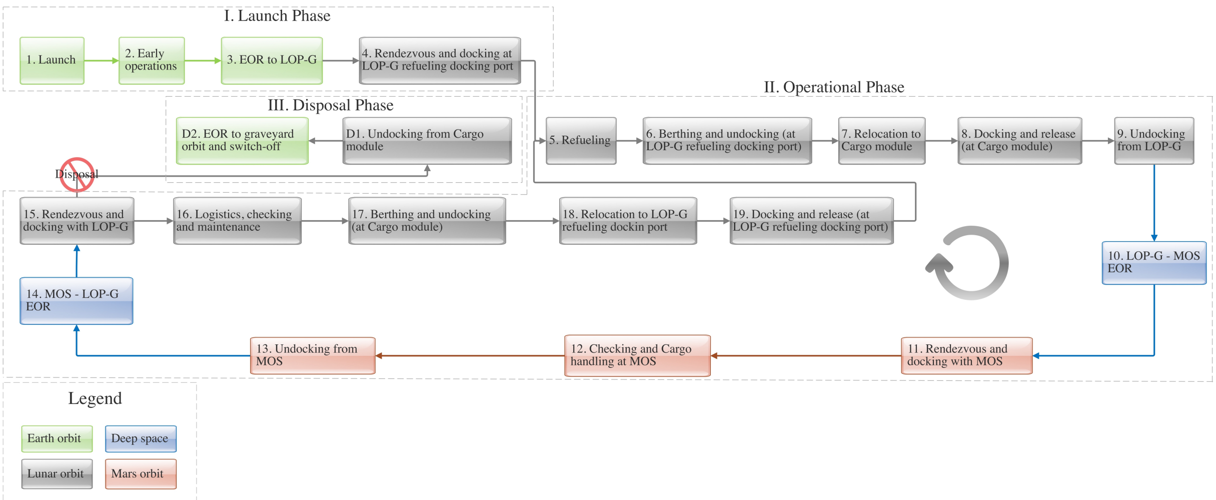



Figure 5.7: Phases Block Diagram **1a**

### 5.4.4 Mission Phases Specification for Scenario 1d

In this section, the phases identified previously in Section 5.3.1 have been studied in detail for Scenario 1d. In particular, only the phases with significant differences from the previous version are reported and specified. In accordance with the considerations made about the Scenario 1a, we have chosen to always perform docking maneuvers as mating operations. Below, the phases characterization from operational point of view.

- *Launch*, *Early operations* and *EOR to LOP-G* are the same as the previous identified.

4 *Rendezvous and docking with Cargo module:*
all the operations required in LOP-G vicinity to dock ICV to Cargo module docking port. Cargo module is docked to LOP-G through the opposite docking port.

5 *Refueling:*
all the operations required to transfer fuel to ICV tank throughout Cargo module.

6 *Maintenance and cargo handling at LOP-G:*
all the operations required to deliver/ retrieve cargo assets according to mission requests and to verify and guarantee the proper functioning of ICV.

7 *Undocking from LOP-G:*
all the operations required to undock Cargo module from LOP-G.

- *LOP-G – MOS EOR*, *Rendezvous and docking with MOS*, *Checking and Cargo handling at MOS*, *Undocking from MOS* and *MOS – LOP-G EOR* are the same as the previous identified.

13 *Rendezvous and docking with LOP-G:*
all the operations required in the LOP-G vicinity to dock Cargo module to LOP-G docking port.

In addition, the disposal operations have been inserted at the end of the operational life of the ICV. The end-of-life is represented by the system switch-off once reached the assigned graveyard orbit. The phases that represent the *Disposal* are the same D1 and D2 presented in Section 5.4.1.

For Table 5.7 and Table 5.8 are valid the same considerations made for the tables in Section 5.4.1. All the phases are shown in order to provide an overview of the whole scenario.

| No. | Phase | Start | End | Initial orbit | Final orbit | Description | Environ ment | Cargo module configuration |
|---|---|---|---|---|---|---|---|---|
| 1. | Launch | Lift-off | Orbit insertion | Ground | LEO | Operations required to put into LEO the ICV | Payload envelope | Not loaded |
| 2. | Early operations | Orbit insertion | ICV ready for EOR | LEO | LEO | Operations required to check the subsystems health status | Earth orbit | Not loaded |
| 3. | EOR to LOP-G | ICV ready for EOR | ICV arrival in LOP-G vicinity | LEO | LOP-G orbit | LEO to LOP-G EOR | Cis-lunar | Not loaded |
| 4. | Rendezvous and docking with Cargo module | ICV arrival in LOP-G vicinity | ICV docked to Cargo module docking port | LOP-G orbit | LOP-G orbit | Operations required in LOP-G vicinity to dock ICV to Cargo module docking port | Lunar orbit | Not loaded |
| 5. | Refueling | ICV docked to Cargo module docking port | ICV refueled | LOP-G orbit | LOP-G orbit | Operations required to transfer fuel to ICV tank throughout Cargo module | Lunar orbit | Not loaded |
| 6. | Maintenance and cargo handling at LOP-G | ICV refueled | Cargo module managed | LOP-G orbit | LOP-G orbit | Operations required to deliver/ retrieve cargo assets according to mission requests and to verify and guarantee the proper functioning of ICV | Lunar orbit | Not loaded |
| 7. | Undocking from LOP-G | Cargo module managed | Cargo module undocked from ICV | LOP-G orbit | LOP-G orbit | Operations required to undock Cargo module from LOP-G | Lunar orbit | Loaded |
| 8. | LOP-G – MOS EOR | Cargo module undocked from LOP-G | ICV arrival in MOS vicinity | LOP-G orbit | MOS orbit | Electric orbit raising required to reach the MOS orbit | Deep space | Loaded |

Table 5.7: Table of phases **1d** (first part)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 9. | Rendezvous and docking with MOS | ICV arrival in MOS vicinity | Cargo module docked to MOS | MOS orbit | MOS orbit | Operations required in MOS vicinity to dock Cargo module with MOS docking port | Mars orbit | Loaded |
| 10. | Checking and Cargo handling at MOS | Cargo module docked to MOS | Cargo module managed | MOS orbit | MOS orbit | Operations required to verify the proper functioning of ICV and to deliver/ retrieve cargo assets | Mars orbit | Loaded |
| 11. | Undocking from MOS | Cargo module managed | Cargo module undocked from MOS | MOS orbit | MOS orbit | Operations required to undock Cargo module from MOS | Mars orbit | Loaded |
| 12. | MOS – LOP-G EOR | Cargo module undocked from MOS | ICV arrival in LOP-G vicinity | MOS orbit | LOP-G orbit | Electric orbit raising required to reach the LOP-G orbit | Deep space | Loaded |
| 13. | Rendezvous and docking with LOP-G | ICV arrival in LOP-G vicinity | Cargo module docked to LOP-G | LOP-G orbit | LOP-G orbit | Operations required in LOP-G vicinity to dock Cargo module with LOP-G docking port | Lunar orbit | Loaded |
| D1. | Undocking from Cargo module | Cargo module docked to LOP-G | ICV undocked from Cargo module | LOP-G orbit | LOP-G orbit | Operations required to undock ICV from Cargo module | Lunar orbit | Not loaded |
| D2. | EOR to graveyard orbit and switch-off | ICV undocked from Cargo module | ICV completely switched off | LOP-G orbit | Graveyard orbit | Electric orbit raising from LOP-G orbit to graveyard orbit and system shutdown | Cis-lunar | Not loaded |

Table 5.8: Table of phases **1d** (second part)

### 5.4.5 Design Reference Mission - 1d

The extended launch phase (represented in Figure 5.8 by the Roman number "I") includes launch, early operations, EOR to LOP-G and rendezvous and docking at LOP-G phases previously described in Section 5.3.3. The only difference specified is the used docking port; in this scenario is required, only for the first contact with the station, to dock directly with the Cargo Module docking port.

At this point, the extended operative phase (represented in Figure 5.8 by the Roman number "II") can begin. Subsequently, the refueling through the Cargo Module, maintenance and cargo handling phases are carried out in sequence. After have accomplished all these operations, the spacecraft, with its cargo module, separates from the station and starts the second electric orbit rising with the aim of reaching the MOS orbit.

All the phases between the EOR to MOS orbit and the EOR returning to LOP-G orbit are the same as the previously described in Section 5.3.3.

Once the lunar station orbit is reached, the rendezvous and docking from deep phase is accomplished at the LOP-G docking port; in such a way the mission cycle can proceed until disposal.

The extended disposal phase (represented in Figure 5.9 by the Roman number "III"), which includes undocking from Cargo Module, EOR to graveyard orbit and system switch-off, represents the ICV end-of-life and the irreversible mission conclusion.

In Figure 5.8 and Figure 5.9 is shown the related DRM.

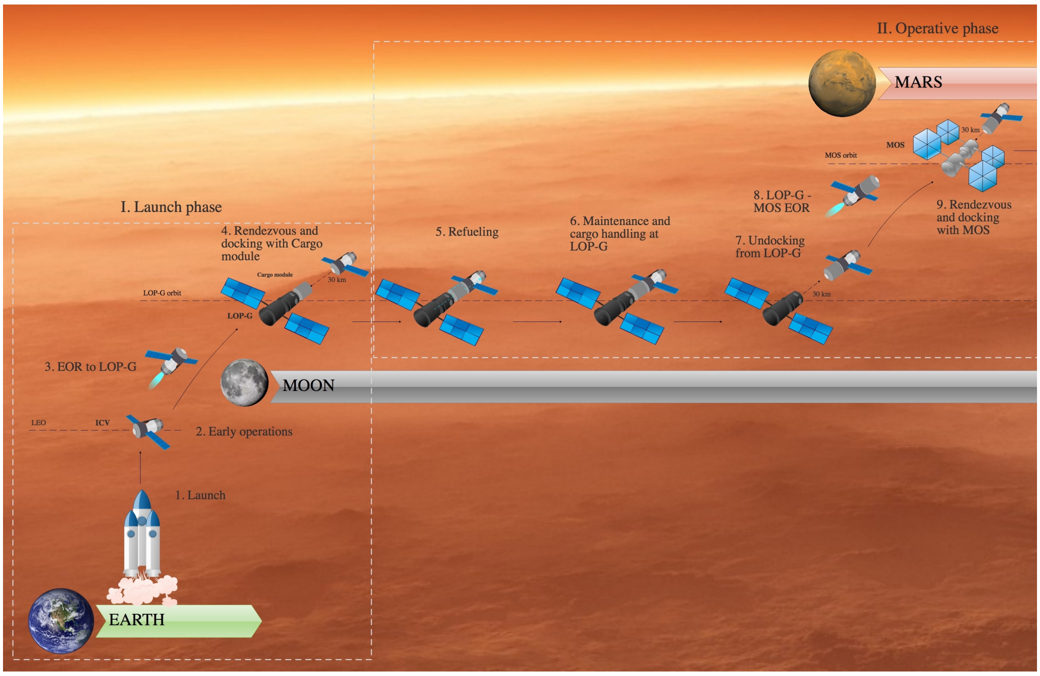



Figure 5.8: Design Reference Mission **1d** (first part)

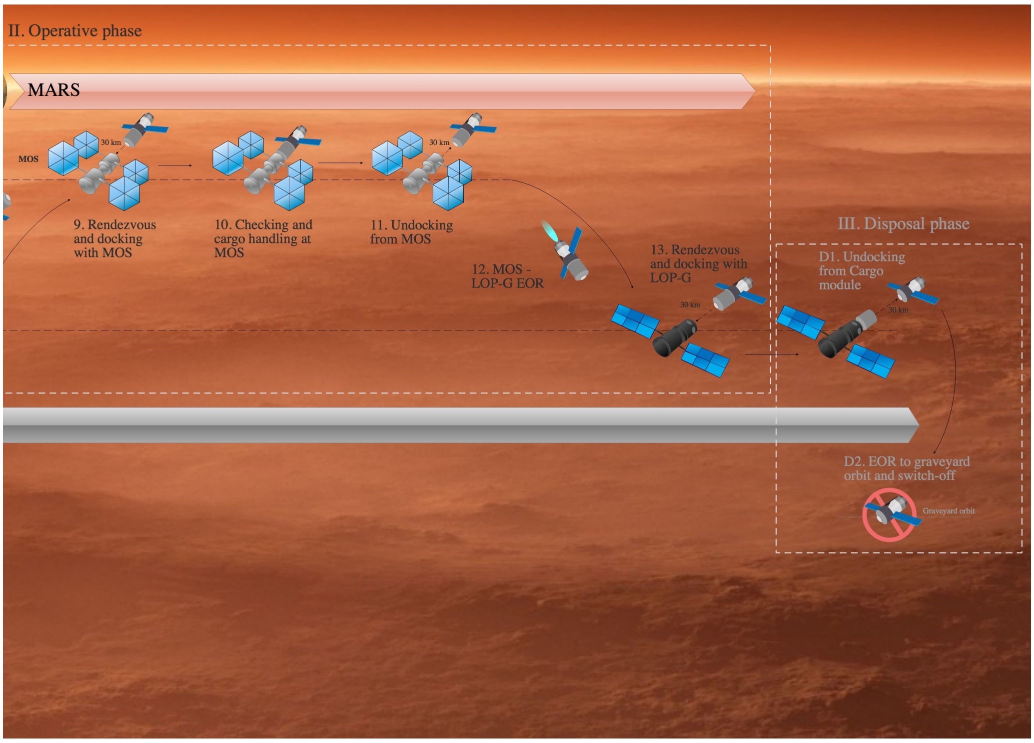



Figure 5.9: Design Reference Mission **1d** (second part)

### 5.4.6 Phases Block Diagram - 1d

In accordance with the considerations made about the Scenario 1a, the first part of the diagram represents the launch phase, which is constituted by the phases necessary to start the effective operating cycle, that are phases 1,2,3 and 4.

The second part of the diagram represents the operational phase, which is constituted by the phases necessary to perform the effective operating cycle of the transportation mission, it is constituted by phases 5 to 13. These ones are repeated identically until the mission end.

The third part of the diagram represents the disposal phase, which is constituted by the phases necessary to perform the disposal and the end-of-life operations. It is constituted by phases D1 and D2.

As reported in the previous Section 5.3.4, a color coding has been used to facilitate understanding of the blocks. In detail, each color corresponds to a reached orbit: green for Earth orbit/cislunar space, grey for Lunar orbit, light blue for Deep space and Orange for Mars orbit. In addition, a stream of arrows guides the succession of the different phases. In Figure 5.10 is shown the relative PBD.

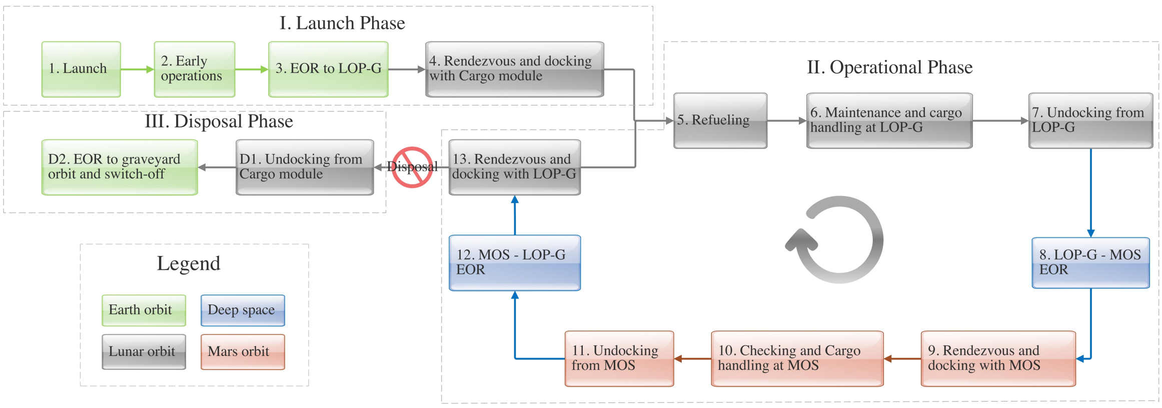



Figure 5.10: Phases Block Diagram **1d**

## 5.5 Modes of Operations

### 5.5.1 Building Blocks Status

As introduced in the previous Section, several building blocks are involved in the ICV mission phases. In particular, each one can be characterized by a different mode of operation along the whole mission, representing the status of the element in all the ICV mission phases. The status of the system represents the operations that the system itself is capable of performing. Three main status have been identified in order to describe the role of the different segments in each mission phase:

***Operational*** constitutes the active status of the segment, during which it is able to participate actively in the mission phase.

***Dormant*** constitutes the passive status of the segment during which the segment is not able to participate actively in the mission phase and provides only a passive contribution to the performance of the mission.

***Safe*** constitutes the contingency status of the segment, i.e. the safe mode. Active and passive operations are required to restore the system. The segment mission is temporarily suspended.

In accordance with the functional analysis conducted in *Chapter 3*, the constitution of the considered building blocks is:

1. Space segment: ICV, Cargo module;
2. Launch segment: Launch Vehicle, Launch Control Station;
3. Ground segment: Mission Control Center, Mission Logistic Center;
4. Lunar space segment: LOP-G, Lunar Navigation Satellites;
5. Mars space segment: MOS, Mars Navigation Satellites, Mars Communication Satellites.

For each segment we can described and characterized the possible status it can enter. They represent a generic condition of the segment and are indicated as follows:

1. Space segment
    - *Operational:* all systems necessary to perform the required operations are active.
    - *Dormant:* only systems necessary to monitor the system and to survive the external environment are active.
2. Launch segment
    - *Operational:* all systems necessary to perform launch operations are active.
3. Ground segment
    - *Operational:* all systems necessary to perform monitor and command operations are active.
    - *Dormant:* only systems necessary to monitor the telemetry data are active.
4. Lunar Space segment
    - *Operational:* all systems necessary to perform the required operations are active.
    - *Dormant:* only systems necessary to monitor rendezvous and docking operations are active.
5. Mars Space segment
    - *Operational:* All systems necessary to perform the required operations are active.
    - *Dormant:* only systems necessary to monitor rendezvous and docking operations are active.

### 5.5.2 ICV Modes of Operations

During each mission phase, the ICV can enter various modes of operations. Unlike the mission phases, which are related to the external environment in which the system operates, we define a mode of operation by establishing which components and equipments are active or not active within that specific mode. Therefore, unlike the mission phases which focus on the external environment, the modes of operations focus on the system itself and how it does work. Different modes of

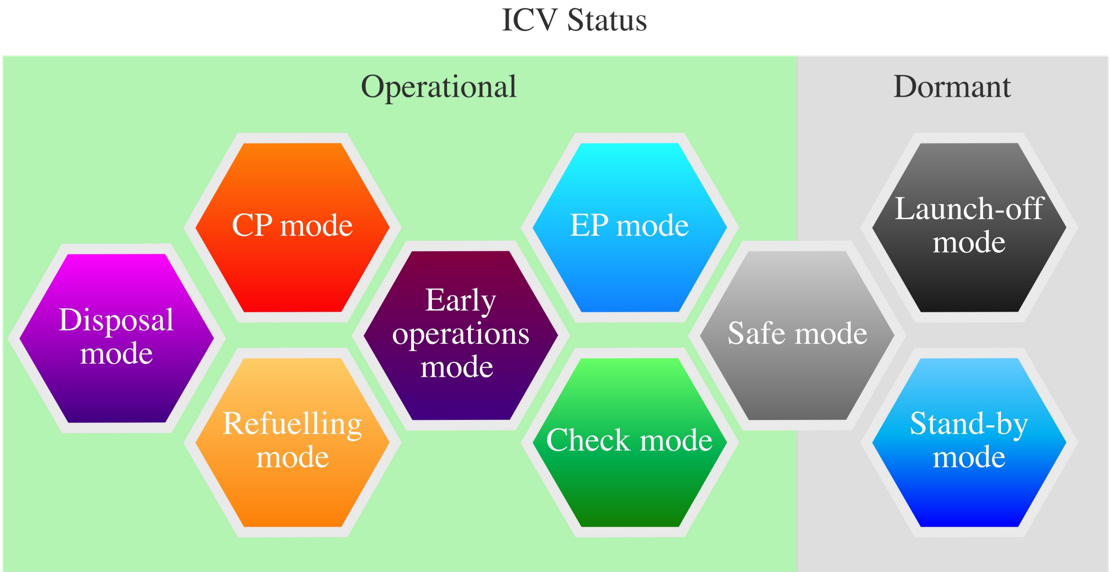



Figure 5.11: Modes of Operations Classification

operation can be envisaged in the same mission phase. The *Figure 5.11* shows all possible modes of operations that can be entered by the ICV during its mission.

ICV components can be activated at different power level in order to unsure the correct execution of the mission phases. Each mode of operation is characterized by a specific components power level configuration. Preliminary, the main power standard identified are:

**F** Full operative, component can be activated up to nominal power level.

**H** High operative, component can be activated up to 2/3 nominal power level.

**L** Low operative, component can be activated up to 1/3 nominal power level.

**I** Not operative, component are inactive.

In accordance to the status type (operational, dormant and safe), the modes of operations that allow the proper execution of the mission have been identified. In the case of modes of operations concerning the operational status, the modes of operations have been specified at a lower level, with the aim of ensuring a more detailed characterization of the fundamental features of the ICV.

- Operational status:

  1. *Check mode*
     ICV components' necessary to check the systems' health status are activated and the data obtained from the analysis are sent to the ground. This operative mode can be activated exclusively when ICV is docked to LOP-G or MOS.
     - *Nominal check mode:* ICV components' health status is checked in sequence (excluding the EP and CP subsystems).
     - *Check report mode:* system check report is processed and sent to the ground.
  2. *Electric propulsion (EP) mode*
     The ICV electric propulsion system is briefly checked, prepared to full operative mode and, after receiving the ignition command, main HETs are activated in full operative mode. Simultaneously, all ICV components necessary to perform the orbit transfer are activated. This operative mode can be activated exclusively when ICV is adequately far from the LOP-G/MOS/ORS with the aim to guarantee the stations' safety. The safety distance from manned and unmanned stations is considered relatively in 30 km and in 5 km.
     - *EP check mode:* a brief check of the main HETs and the feeding system's health status is performed.
     - *Idle mode:* main HETs and the feeding system are prepared to full operative mode and ready for receive the ignition command.
     - *EOR mode:* main HETs are activated at full operative mode and all ICV components necessary to perform the orbit transfer are activated.
  3. *Chemical propulsion (CP) mode*
     The ICV chemical propulsion system is activated to perform the whole rendezvous phase and docking interface is activated to conclude the attachment to the stations. This operative mode can be activated when ICV is adequately close to the LOP-G/MOS/ORS with the aim to ensure adequate attitude and orbit control. The close distance from manned and unmanned stations is considered relatively in 30 km and in 5 km.
     - *CP maneuvers mode:* ICV chemical propulsion system is activated to perform close rendezvous, final approach, first and second hovering maneuvers. Moreover, attitude control system and its actuators are in full operative mode.

  - *Mating mode:* berthing interface is exploited to perform the attachment between grasping mechanism and LOP-G robotic arm (if present). The operational berthing distance is considered in 2 m. Docking interface is activated to perform the attachment to the LOP-G/MOS/ORS. The operational docking distance is considered in 0 m.

4. *Refueling mode*
   The ICV fluid plane is aligned, connections are established and valves are sealed; ICV tanks are filled and fluid plane disconnected. The correct execution of the operations is verified. This operative mode can be activated exclusively when ICV is docked to LOP-G/ORS refueling docking port and docking interface is active.

   - *Connection & sealing mode:* ICV fluid plane is aligned with LOP-G/ORS fluid plane, all connections are established and the valves are sealed.
   - *Tanks filling mode:* fuel is pumped by the LOP-G/ORS refueling system to the ICV tanks and, at the end of the procedure, all the fluid connections are disconnected.
   - *Refueling check mode:* the correct ICV tanks filling and the fluid plane disconnection are verified.

5. *Early operations mode*
   ICV components' are activated, orbit is determined and the attitude is acquired for the first time, a test orbit change is performed with the aim to control and calibrate the concerned components. This operative mode can be activated exclusively after separation from launcher, ICV inserted into LEO.

   - *Switch-on mode:* ICV components' are activated after Launch-off mode (excluding the EP and CP subsystems).
   - *Orbit determination & attitude acquisition mode:* ICV Orbit is determined and the attitude is acquired for the first time with the aim to check the dedicated components.
   - *Orbit change mode:* electrical and chemical propulsion systems are activated for the first time with the aim to check the dedicated components.
   - *Calibration & control mode:* orbit and attitude are once more acquired with the aim to control the correct functioning of the propulsion systems and to calibrate the attitude and communication systems.

6. *Disposal mode*
   ICV components' are activated at low power level to perform the transfer towards the graveyard orbit. The minimum amount of fuel required to perform the transfer is present in the tanks. In graveyard orbit, the final shutdown of the entire system is executed. This operative mode can be activated exclusively when ICV is separated from LOP-G, is located in cislunar orbit and his operational life is ended.
   - *Disposal transfer mode:* main HETs are activated at low operative mode. All ICV component's necessary to perform the orbit transfer are activated at the lowest possible power level and with the sole purpose of reaching the graveyard orbit.
   - *Switch-off mode:* all ICV component's are switched off and no longer recoverable.

- Dormant status:

  7 *Stand-by mode:* ICV component's necessary to monitor the system and to survive the external environment are active with the sole purpose of protecting the spacecraft. In addition, the communication system is activated at low operative mode to allow the commands reception.

  8 *Launch-off mode:* ICV is allocated in the launcher. The clamping interface is engaged end OBC is activated at low power level in order to recognize the separation signal. All others components is in not operative mode.

- Safety Status:

  9 *Safe mode*
  Solar arrays are fully oriented towards sun, all non-essential components are deactivated, a system safety check is performed and telemetry data are sent to the ground. This operative mode can be activated at any time. Power system and AOCS are considered essential components, their non-critical failures are bypassed through redundancies; critical failures of these components cause the loss of the mission. Safe mode involves failures mainly related to thermal control and communication system. The main purpose of this mode is to safely reach LOP-G/ORS in order to perform the necessary maintenance operations.
  - *Sun orientation mode:* double side solar arrays orientation is modified in order to get as much sun exposure as possible with the objective of supplying the maximum possible electric power to the spacecraft.

– *Safety check mode:* all non-essential components are deactivated, essential components are activated at low power level and a check of the subsystem affected by the anomaly is performed.
– *Safety report mode:* safety check report is processed and sent to the nearest station.

In Figure 5.12 the Operative Modes of Operations are shown graphically, to each block corresponds a MoO with the related sub-modes. The used colors have the sole purpose of qualitatively representing, as faithfully as possible, the active components.


Figure 5.12: ICV Operative Modes of Operations

In the following Table 5.9 and Table 5.10 the MoO have been characterized and the active components have been indicated. Furthermore, for each component, the coding presented in the legend has been used in order to provide an indication of the usable power level of the single component.

**Legend:**

F Component can be activated up to nominal power level (full operative mode)

H Component can be activated up to 2/3 nominal power level (high operative mode)

L Component can be activated up to 1/3 nominal power level (low operative mode)

I Component inactive (not operative)

A Component is active (active mode)
"active mode" concerns only interface status.

O Component is operative (operative mode)
"operative mode" concerns only solar arrays status and indicates that they are active and able to supply the required power.

| Modes / Components | Stand-by | Launch-off | Check | Safe | EP | CP | Refueling | Disposal |
|---|---|---|---|---|---|---|---|---|
| PPU | I | I | I | L | F | I | I | L |
| Thruster Units | I | I | I | L | F | I | I | L |
| Feeding system | I | I | I | L | F | I | I | L |
| Orbit sensors | I | I | H | L | F | F | I | H |
| Attitude sensors | I | I | H | L | F | F | I | H |
| AOCS actuators* | I | I | H | L | F | F | I | H |
| AOCS OBC | I | I | H | L | F | F | I | H |
| Solar arrays | O | I | O | O | O | O | O | O |
| Batteries | L | I | H | L | F | F | F | H |
| PCDU | L | I | H | L | F | F | H | H |
| Heat pipes | H | I | H | I | F | F | H | H |
| Radiators | H | I | H | I | F | F | H | H |
| Electrical heaters | H | I | H | I | F | F | H | H |
| TCS OBC | H | I | H | I | F | F | H | H |
| Temperature sensors | H | I | H | I | F | F | H | H |
| Docking I/F | A | I | A | A | I | A | A | I |

Table 5.9: Modes of Operations Characterization (first part)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Fluid Plane | I | I | I | I | I | I | A | I |
| Fluid couplings | I | I | I | I | I | I | A | I |
| Electrical connector | I | I | I | I | I | I | A | I |
| Refueling valves | I | I | I | I | I | I | A | I |
| Commands decoder | L | I | H | I | F | F | H | H |
| OBC | L | L | F | L | F | F | H | H |
| Data Storage Unit | L | I | H | I | F | F | H | H |
| RIU | L | I | H | I | F | F | H | H |
| Antennas | L | I | H | I | F | F | H | H |
| Receiver | L | I | H | I | F | F | H | H |
| Transmitter | I | I | H | I | F | F | H | H |
| Auto-tracking equipment | I | I | H | I | F | F | I | H |
| Data bus | L | I | H | I | F | F | H | H |

* In "AOCS actuators" is included also the feeding system.

Table 5.10: Modes of Operations Characterization (second part)

At this point all the possible Modes of Operations in which the ICV can be entered have been described in their main characteristics. The two scenarios previously introduced can be analyzed subsequently in their operational features.

### 5.5.3 Analysis of Scenario 1a

#### Building Blocks Status during operations

Remembering the phases described previously in Section 5.4.3, the segment concerned each phase have been identified. In addition, the status of the various segments involved has also been specified, the result are shown in the following Table 5.11. Safety status has not been reported in the table since it is strictly a contingency status. Obviously, each segment can enter this kind of status at any time during any phase.

| Phases \ Segments | Space | Launch | Ground | Lunar space | Mars space |
|---|---|---|---|---|---|
| 1. Launch | D | O | O | | |
| 2. Early operations | O | | O | | |
| 3. EOR to LOP-G | O | | D | | |
| 4. Rendezvous and docking at the LOP-G refueling docking port | O | | D | D | |
| 5. Refueling | D | | | O | |
| 6. Berthing and undocking (at LOP-G refueling docking port) | D | | | O | |
| 7. Relocation to Cargo module | D | | | O | |
| 8. Docking and release (at Cargo module) | D | | | O | |
| 9. Undocking from LOP-G | O | | D | D | |
| 10. LOP-G – MOS EOR | O | | D | | |
| 11. Rendezvous and docking with MOS | O | | D | | D |
| 12. Checking and Cargo handling at MOS | D | | O | | O |
| 13. Undocking from MOS | O | | D | | D |
| 14. MOS – LOP-G EOR | O | | D | | |
| 15. Rendezvous and docking with LOP-G | O | | D | D | |
| 16. Logistics, checking and maintenance | D | | O | O | |
| 17. Berthing and undocking (at Cargo module) | D | | | O | |
| 18. Relocation to LOP-G refueling docking port | D | | | O | |
| 19. Docking and release (at LOP-G refueling docking port) | D | | | O | |
| D1. Undocking from Cargo module | O | | D | D | |
| D2. EOR to graveyard orbit and switch-off | O | | D | | |

Table 5.11: Building Blocks Status for Scenario **1a**

### ICV MoO during operations

Shifting the attention to the ICV, the Modes of Operations that interest each phase have been analyzed in the following Table 5.12. Analogous to the considerations made beforehand regarding the Safety status, also the "Safe mode" has not been reported in the table since it is strictly a contingency mode and the ICV can enter this kind of mode at any time during any phase.

| Phases \ Modes | Launch-off | Early op. | Stand-by | Check | EP | CP | Ref. | Disposal |
|---|---|---|---|---|---|---|---|---|
| 1. Launch | X | | | | | | | |
| 2. Early operations | | X | | | | | | |
| 3. EOR to LOP-G | | | | | X | | | |
| 4. Rendezvous and docking at the LOP-G refueling docking port | | | | | | X | | |
| 5. Refueling | | | | | | | X | |
| 6. Berthing and undocking (at LOP-G refueling docking port) | | | X | | | | | |
| 7. Relocation to Cargo module | | | X | | | | | |
| 8. Docking and release (at Cargo module) | | | X | | | | | |
| 9. Undocking from LOP-G | | | | | | X | | |
| 10. LOP-G – MOS EOR | | | | | X | | | |
| 11. Rendezvous and docking with MOS | | | | | | X | | |
| 12. Checking and Cargo handling at MOS | | | X | X | | | | |
| 13. Undocking from MOS | | | | | | X | | |
| 14. MOS – LOP-G EOR | | | | | X | | | |
| 15. Rendezvous and docking with LOP-G | | | | | | X | | |
| 16. Logistics, checking and maintenance | | | | X | | | | |
| 17. Berthing and undocking (at Cargo module) | | | X | | | | | |
| 18. Relocation to LOP-G refueling docking port | | | X | | | | | |
| 19. Docking and release (at LOP-G refueling docking port) | | | X | | | | | |
| D1. Undocking from Cargo module | | | | | | X | | |
| D2. EOR to graveyard orbit and switch-off | | | | | | | | X |

Table 5.12: Modes of Operations for Scenario **1a**

### ICV Modes Transition

The transition stable has been developed with the aim of guaranteeing the allowed passage from one mode to another. Furthermore, the transition events have been represented for each mode switch. In following Table 5.13 are shown the information mentioned above:

| Modes | | | Transition event(s) |
|---|---|---|---|
| No. | From | to | |
| 1. | Launch-off | Early operations | ICV is inserted into LEO |
| 2. | Early operations | EP | Early operations are successfully completed |
| 3. | EP | CP | - ICV reach the LOP-G proximity<br>- ICV reach the MOS proximity |
| 4. | CP | EP | - ICV reach the safety distance from LOP-G<br>- ICV reach the safety distance from MOS |
| 5. | CP | Stand-by | ICV is docked to MOS |
| 6. | Stand-by | CP | ICV is docked to Cargo module and ready for departure |
| 7. | Stand-by | Check | - ICV docked to LOP-G<br>- End of Cargo module handling at MOS |
| 8. | Check | Stand-by | ICV is docked to LOP-G and checked |
| 9. | Check | CP | ICV is docked to MOS, checked and ready for departure |
| 10. | Stand-by | Refueling | ICV is docked to LOP-G refueling docking port |
| 11. | Refueling | Stand-by | ICV fuel tanks are filled |
| 12. | CP | Refueling | ICV is docked to LOP-G refueling docking port |
| 13. | CP | Disposal | - ICV reach the safety distance from LOP-G<br>- ICV end of life |
| 14. | All | Safe | Anomaly/failure is detected |
| 15. | Safe | All | Anomaly/failure is neutralized or secured |

Table 5.13: Modes Transition Table **1a**

The sole transitions between Modes of Operations are those shown in the Table 5.13, every other transition is not allowed for security reasons or mission constrains.

The Modes Transition Diagram shows graphically the transition ways between the different Modes of Operations. The numbers are referred at the previous Table 5.13. The main feature of this diagram is the pivotal representation of the "Safe mode". It is strictly a contingency mode and the ICV can enter this kind of mode at any time from any other MoO, with the exception of "Launch-off mode" (ICV is located into the launcher) and "Disposal mode" (ICV end-of-life is reached).

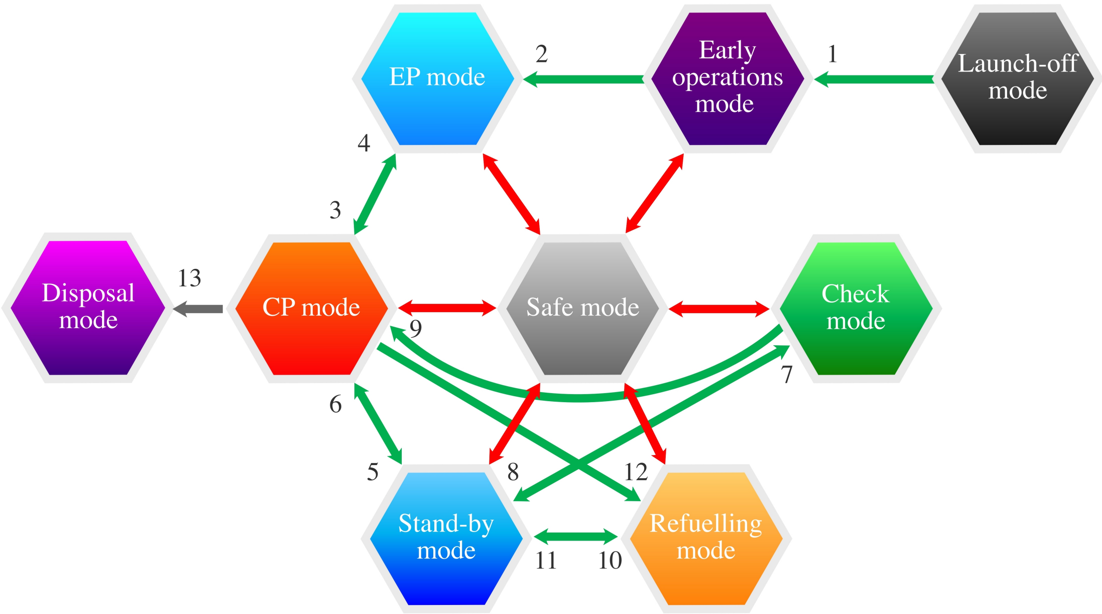



Figure 5.13: Modes Transition Diagram **1a**

## 5.5.4 Analysis of Scenario 1d

### Building Blocks Status during operations

Remembering the phases described previously in Section 5.4.4, the segment concerned each phase have been identified. In addition, the status of the various segments involved has also been specified, the result are shown in the following Table 5.14. As explained above, "Safety status" has not been reported in the table since it is strictly a contingency status. Obviously, each segment can enter this kind of status at any time during any phase

| Phases \ Segments | Space | Launch | Ground | Lunar space | Mars space |
|---|---|---|---|---|---|
| 1. Launch | D | O | O | | |
| 2. Early operations | O | | O | | |
| 3. EOR to LOP-G | O | | D | | |
| 4. Rendezvous and docking with Cargo module | O | | D | D | |
| 5. Refueling | D | | | O | |
| 6. Maintenance and cargo handling at LOP-G | D | | | O | |
| 7. Undocking from LOP-G | O | | D | D | |
| 8. LOP-G – MOS EOR | O | | D | | |
| 9. Rendezvous and docking with MOS | O | | D | | D |
| 10. Checking and Cargo handling at MOS | D | | O | | O |
| 11. Undocking from MOS | O | | D | | D |
| 12. MOS – LOP-G EOR | O | | D | | |
| 13. Rendezvous and docking with LOP-G | O | | D | D | |
| D1. Undocking from Cargo module | O | | D | | |
| D2. EOR to graveyard orbit and switch-off | O | | D | | |

Table 5.14: Building Blocks Status for Scenario **1d**

### ICV MoO during operations

Shifting the attention to the ICV, the Modes of Operations that interest each phase have been analyzed in the following Table 5.15. Analogous to the considerations made beforehand regarding the "Safety status" and the Scenario 1a, also the "Safe mode" has not been reported in the table since it is strictly a contingency mode and the ICV can enter this kind of mode at any time during any phase.

| Phases \ Modes | Launch-off | Early op. | Stand-by | Check | EP | CP | Ref. | Disposal |
|---|---|---|---|---|---|---|---|---|
| 1. Launch | X | | | | | | | |
| 2. Early operations | | X | | | | | | |
| 3. EOR to LOP-G | | | | | X | | | |
| 4. Rendezvous and docking with Cargo module | | | | | | X | | |
| 5. Refueling | | | | | | | X | |
| 6. Maintenance and cargo handling at LOP-G | | | X | X | | | | |
| 7. Undocking from LOP-G | | | | | | X | | |
| 8. LOP-G – MOS EOR | | | | | X | | | |
| 9. Rendezvous and docking with MOS | | | | | | X | | |
| 10. Checking and Cargo handling at MOS | | | X | X | | | | |
| 11. Undocking from MOS | | | | | | X | | |
| 12. MOS – LOP-G EOR | | | | | X | | | |
| 13. Rendezvous and docking with LOP-G | | | | | | X | | |
| D1. Undocking from Cargo module | | | | | | X | | |
| D2. EOR to graveyard orbit and switch-off | | | | | | | | X |

Table 5.15: Modes of Operations for Scenario **1d**

### ICV Modes Transition

As explained above, the transition stable has been developed with the aim of guaranteeing the allowed passage from one mode to another. Furthermore, the transition events have been represented for each mode switch. In following Table 5.16 are shown the information mentioned above:

| Modes | | | Transition event(s) |
|---|---|---|---|
| No. | From | to | |
| 1. | Launch-off | Early operations | ICV is inserted into LEO |
| 2. | Early operations | EP | Early operations are successfully completed |
| 3. | EP | CP | - ICV reach the LOP-G proximity<br>- ICV reach the MOS proximity |
| 4. | CP | EP | - ICV reach the safety distance from LOP-G<br>- ICV reach the safety distance from MOS |
| 5. | CP | Stand-by | ICV is docked to MOS |
| 6. | Stand-by | Check | - ICV is docked to LOP-G and tanks are filled<br>- End of Cargo module handling at MOS |
| 7. | Check | CP | -ICV is docked to Cargo module, checked and ready for departure<br>-ICV is docked to MOS, checked and ready for departure |
| 8. | Refueling | Stand-by | ICV is docked to Cargo module and fuel tanks are filled |
| 9. | CP | Refueling | ICV is docked to Cargo module and ready for refueling |
| 10. | CP | Disposal | - ICV reach the safety distance from LOP-G<br>- ICV end of life |
| 11. | All | Safe | Anomaly/failure is detected |
| 12. | Safe | All | Anomaly/failure is neutralized or secured |

Table 5.16: Modes Transition Table **1d**

As the previous considerations for Scenario 1a, the sole transitions between Modes of Operations are those shown in the Table 5.16, every other transition is not allowed for security reasons or mission constrains.

The Modes Transition Diagram shows graphically the transition ways between the different Modes of Operations. The numbers are referred at the previous Table 5.16. The main feature of this diagram is the pivotal representation of the "Safe mode". It is strictly a contingency mode and the ICV can enter this kind of mode at any time from any other MoO, with the exception of "Launch-off mode" (ICV is located into the launcher) and "Disposal mode" (ICV end-of-life is reached).

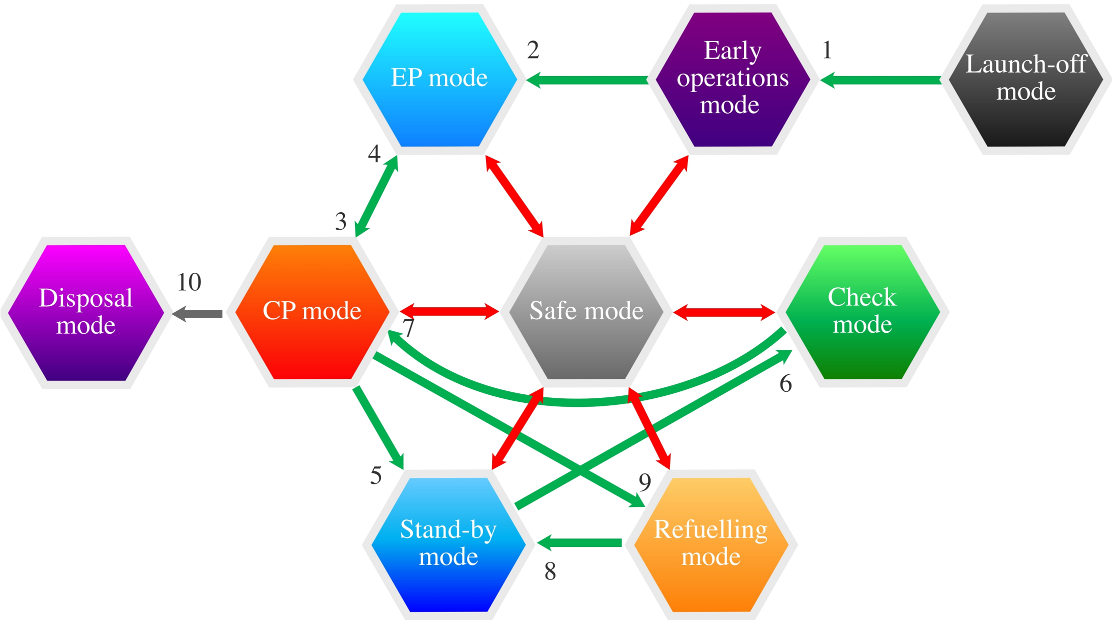



Figure 5.14: Modes Transition Diagram **1d**

### 5.5.5 Operational Requirements

Additional requirements arise from the analysis of the Modes of Operations. They are the *Operational Requirements* and contains recommendations related to the system operability. They express which modes of operation the system shall be able to enter during a specific phase. They also establish the equipment that is active or not in a specific mode and its power level range. For examples:

- *The ICV shall be able to enter in Check mode in the "Checking and Cargo handling at MOS" phase;*
- *In Check mode the Thruster Units shall be inactive;*
- *In Check mode Orbit Sensors shall be active at a power range between 1/3 and 2/3 of the nominal power level;*
- *The ICV shall be able to enter in EP mode in the "EOR to LOP-G" phase;*
- *In EP mode the PPU shall be active at a power range between the nominal power level and 2/3 of the nominal power level;*
- *In EP mode Docking I/F shall be inactive.*

# Chapter 6

# Trade-off Analysis

A cost-effective and safe system must provide a particular kind of balance between effectiveness and cost: the system must provide the most effectiveness for the resources expended, or equivalently, it must be the least expensive for the effectiveness it provides. This condition is a weak one because there are usually many designs that meet the condition. Design trade studies, an important part of the systems engineering process, often attempt to find designs that provide a better combination of the various dimensions of cost and effectiveness. Trade-off analysis is a method to accomplish design trade studies. Trade-off analysis can be applied at different level of the system design process [12, 13].

## 6.1 Figures of Merits (FoM)

Figures of Merits are a numerical value representing a measure of effectiveness, efficiency, performance or other important factor, and ascertained or approximated from analysis, appraisal, or estimation techniques.
The Figures of Merits are the fundamental basis of the trade-off analysis and they must be chosen with considerable accuracy. Scenario 1a and Scenario 1d (Section 5.4.1 and Section 5.4.4) shows different features. Different refueling operations suggest the necessity to evaluate these differences through a dedicated index. In relation of this, the possible necessity to implement new functions (e.g. LOP-G refueling capability) has been introduced through a dedicated index. In addition, the two scenarios present different cargo capability. Mass, power and cost, being directly proportional to each other in a first approximation, have been taken into account in a single index called "mass". Finally, since the LOP-G and the MOS are manned stations, an index has been introduced that measures the crew safety in relation to the operations performed by the ICV. Therefore, the following Figures

of Merits have been chosen:

- The **mass** index is proportional to the spacecraft cost and power, it is also related to the type of mission, system complexity and maturity level of the utilized technology. Mass index is numerically equal to the mass.
- The **refueling complexity** is related to the system complexity of refueling operations and maturity level of the utilized technology for refueling. Using little-known technologies such as refueling through Cargo Module increase the refueling complexity, whereas a direct refueling interface between the ICV and the servicing system decrease the index. Refueling complexity index is equal to 0 in case of direct refueling interface and equal to 1 in case of refueling through Cargo Module.
- The **new functions exploitation** index is an important FoM. Need for functions not yet foreseen in current concepts such as refueling operations at LOP-G increases the index. New functions exploitation index is directly proportional to the number of new functions introduced.
- The **crew safety** index decreases when refueling operations occur while the crew is on board the refueling infrastructure and increase when refueling is performed at a dedicated unmanned system. Crew safety is equal to 0 in case of refueling operations occur at the LOP-G when crew is on board the station and equal to 1 in case of refueling operations occur an unmanned station.
- The **maximum cargo capacity** index is related to number of tons the system can transfer in compliance with following constrains:
  - maximum number of thrusters in the propulsion configuration shall not exceed 35 units;
  - maximum end-to-end transfer time shall not exceed 3 years.

### 6.1.1 Weight Factor Estimation

In order to estimate a weight factor per each FoM (i.e. establish how much each FoM is relevant in comparison with all others), it may be useful to compare two FoM at a time instead of one FoM with all others at the same time. This simple task can be accomplished through a matrix. The boxes that present the value 1 indicate that the FoM on the row is more relevant than than the FoM on the column. On the opposite, the boxes that present the value 0 indicate that the

FoM on the row is less relevant than than the FoM on the column. Obviously, the obtained matrix is symmetrical. Weight Factor does not need to be normalized to 10 because, having 5 Figures of Merits, the total sum of the single weights is exactly equal to 10. The Weight Factors have been estimated through the following Table 6.1.

| FoM | Mass | Refueling complexity | New functions exploitation | Crew Safety | Maximum Cargo Capacity | **Rank/ Weight Factor** |
|---|---|---|---|---|---|---|
| Mass | | 1 | 1 | 0 | 1 | **3** |
| Refueling complexity | 0 | | 0 | 0 | 1 | **1** |
| New functions exploitation | 0 | 1 | | 0 | 0 | **1** |
| Crew Safety | 1 | 1 | 1 | | 1 | **4** |
| Maximum Cargo Capacity | 0 | 0 | 1 | 0 | | **1** |
| Total weight factor | | | | | | **10** |

Table 6.1: Weight Factor Estimation

From the previous table results:

- To maximize "Crew Safety" index is always a priority compared to all others FoM;
- Reducing "Mass" index is a priority compared to "Refueling Complexity" index and "New Functions Exploitation" index but it is minor compared to "Crew Safety" index and "Maximum Cargo Capacity" index;
- Reducing "Refueling Complexity" index is a priority compared to "Maximum Cargo Capacity" index but it is minor compared to "Mass" index, "New Functions Exploitation" and "Crew Safety" index;

- Reducing "New Functions Exploitation" is a priority compared to "Refueling Complexity" index but it is minor compared to "Mass" index, "Crew Safety" index and "Maximum Cargo Capacity";
- Increasing "Maximum Cargo Capacity" index is a priority compared to "New Functions Exploitation" index but it is minor compared to "Mass" index, "Refueling Complexity" index and "Crew Safety" index.

In accordance with the considerations made above, the index with higher weight factor (4) is the "Safety Crew". Sequentially the others four index: "Mass" (3), "Refueling Complexity" (1), "New Functions Exploitation" (1) and "Maximum Cargo Capacity" (1).

## 6.2 Mission Budgets

In this section, the design process followed to preliminary size the different platforms is briefly described and then the main results are presented. The focal point of the design analysis is twofold. On one side, the ICV is mission-driven, in order to be compliant with the mission needs and constraints, that are: maximum mission duration scheduled in 3 years (1095 days) and maximum number of thrusters set in 35 units. On the other hand, the results analysis is technology-driven: the goal is to optimize the design of all the two platforms to address the ICV development activities, identifying a common optimal working point of the HETs. For each mission scenario, the design results presented in the follows have been obtained exploiting a multi-input (concerned orbits and payload mass configurations) multi-output tool, i.e. the Mission and Space Systems (MISS) design tool [16]. Scenario 1a and 1d will present the same ICV budgets since they present equally input data.

The analysis have been carried out for four payload mass configurations: 5000 kg, 10000 kg, 15000 kg and 20000 kg. Concerning the scenario 1a, only the 5000 kg configuration (yellow points series in Figure 6.1 and Figure 6.2) and the 10000 kg configuration (red points series in Figure 6.1 and Figure 6.2) have been compliant with the constraints introduced above. The following trade-off analysis will be carried out exclusively for 5000 kg payload mass configuration.

| **Scenario 1a/1d** | |
|---|---|
| Working point | 12 |
| Isp | 3100 s |
| Thrusters tot. | 22 |
| Active thrusters | 10 |
| $\Delta$t | 765.4625 days |
| $\Delta$v | 9.3672 m/s |
| Tot. wet mass | $6.2711 \cdot 10^4$ kg |
| Fuel mass | $1.9106 \cdot 10^4$ kg |
| Power | 200 kW |

Table 6.2: Mission Budgets for Scenario **1a** and **1d**

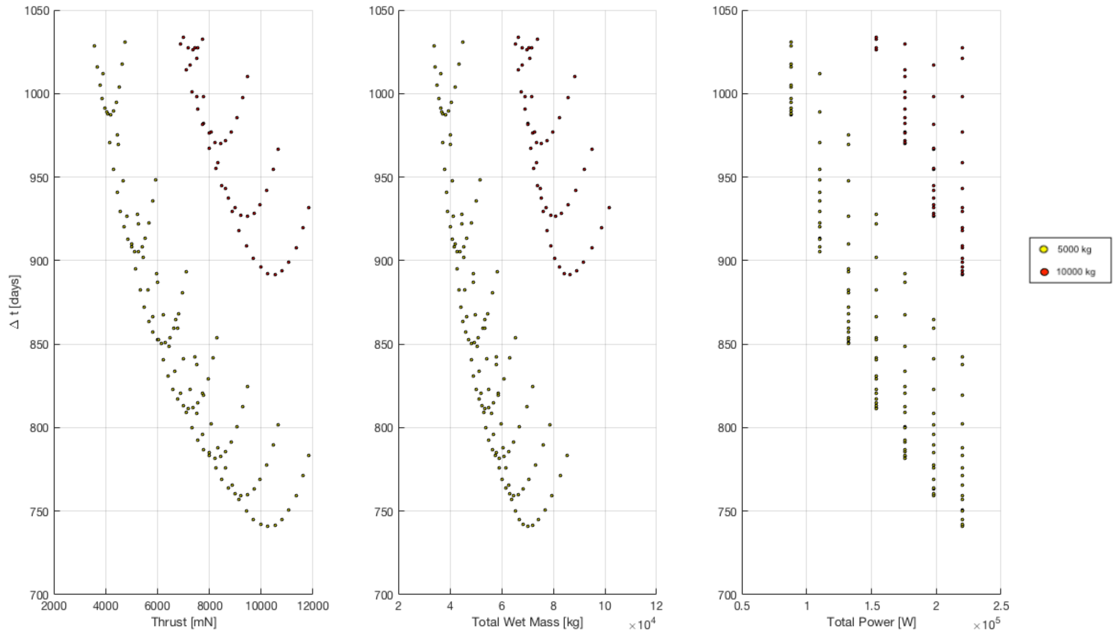



Figure 6.1: $\Delta$v - Thrust/Tot. wet mass/Power Diagram

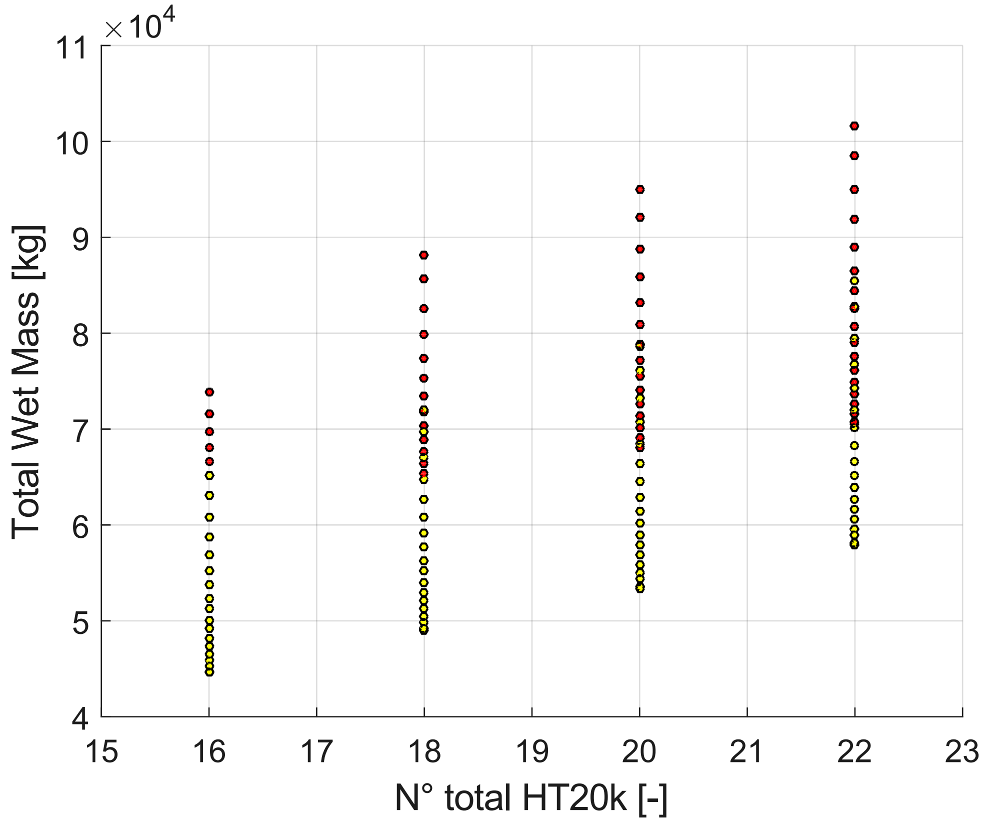



Figure 6.2: Tot. wet mass - N°total HT20K Diagram

## 6.3 Trade-off Results

The value index (V) is calculated using eq.(6.1) (first equation, see below) with the normalized parameters ($P_i$) obtained through eq. (6.2) and (6.3) (respectively second and third equation, see below), where $p_i$ is score index referred to the i-th option. Equation (6.2) is applied to "Crew Safety" and "Maximum Cargo Capacity" because they are proportional to scenario reliability and effectiveness. Equation (6.3) is applied to "Mass", "Refueling complexity" and "New functions exploitation" that are inversely proportional to scenario reliability and effectiveness.

$$V = \frac{\sum P_i \cdot w_i}{\sum w_i} \tag{6.1}$$

$$P_i = \frac{p_i}{max(p)} \cdot 10 \tag{6.2}$$

$$P_i = 10 - \frac{p_i}{max(p)} \cdot 10 \tag{6.3}$$

It should be noted that the assigned scores are values, which are all different for the various FoM considered in the evaluation. It is mandatory that scores are expressed as percentages.

### 6.3.1 Results for Scenario 1a

In the following Table 6.3 the FoM presented in Section 6.1 have been evaluated according to the described judgment criteria.

| FoM | Weight ($w_i$) | Index Score ($p_i$) | Comments |
|---|---|---|---|
| Mass | **3** | $6.2711 * 10^4$ | Dry mass [kg] of the ICV excluding the Cargo Module |
| Refueling complexity | **1** | 0 | Refueling occur through direct interface between the ICV and the LOP-G |
| New functions exploitation | **1** | 2 | 2 new functions assigned to the LOP-G are present: refueling operations and ICV relocation through the robotic arm |
| Crew Safety | **4** | 0 | Refueling operations occur at the LOP-G when crew is on board the station |
| Maximum Cargo Capacity | **1** | 10000 | Cargo carrying capabilities is up to 10000 kg |

Table 6.3: Scores of the different Figures of Merits **1a**

The following Table 6.4 has been obtained by applying the proper equation among eq.(6.2) and eq.(6.3), and eq.(6.3) to the index score $p_i$ obtained above.

| FoM | Weight ($w_i$) | Normalized parameter ($P_i$) | Result (V) |
|---|---|---|---|
| Mass | **3** | 1.41 | 4.23 |
| Refueling complexity | **1** | 10 | 10 |
| New functions exploitation | **1** | 2 | 0 |
| Crew Safety | **4** | 0 | 0 |
| Maximum Cargo Capacity | **1** | 10 | 10 |
| | | | 24.23/10 ≅ **2.40** |

Table 6.4: Results for Scenario **1a**

### 6.3.2 Results for Scenario 1d

In the following Table 6.5 the FoM presented in Section 6.1 have been evaluated according to the described judgment criteria.

| FoM | Weight ($w_i$) | Index Score ($p_i$) | Comments |
|---|---|---|---|
| Mass | **3** | $6.2711 * 10^4$ | Dry mass [kg] of the ICV excluding the Cargo Module |
| Refueling complexity | **1** | 1 | Refueling occur through the Cargo Module |
| New functions exploitation | **1** | 1 | 1 new function assigned to the LOP-G are present: refueling operations |
| Crew Safety | **4** | 0 | Refueling operations occur at the LOP-G when crew is on board the station |
| Maximum Cargo Capacity | **1** | 10000 | Cargo carrying capabilities is up to 10000 kg |

Table 6.5: Scores of the different Figures of Merits **1d**

The following Table 6.6 has been obtained by applying the proper equation among eq.(6.2) and eq.(6.3), and eq.(6.3) to the index score $p_i$ obtained above.

| FoM | Weight ($w_i$) | Normalized parameter ($P_i$) | Result (V) |
|---|---|---|---|
| Mass | **3** | 1.41 | 4.23 |
| Refueling complexity | **1** | 0 | 0 |
| New functions exploitation | **1** | 5 | 5 |
| Crew Safety | **4** | 0 | 0 |
| Maximum Cargo Capacity | **1** | 10 | 10 |
| | | | 19.23/10 ≅ **1.90** |

Table 6.6: Results for Scenario **1d**

### 6.3.3 Trade-off Conclusion

The value index (V) was calculated for all mission scenario options previously presented in Chapter 5. Results are reported in the table below. The highest value was achieved by scenario **1a**.

| **Scenario** | **Value index (V)** |
|---|---|
| 1a | 2.40 |
| 1d | 1.90 |

Table 6.7: Trade-off Conclusion table

As shown in Table 6.7, scenarios 1a provide solution more reliable and efficient rather than scenarios 1d.

# Conclusion

The presented study has carried out the analysis of cargo transfer scenario of an high-power electric spacecraft. The analysis proposed involves both the functional and operational aspects of the mission by means of two main iterative and recursive processes: the Functional Analysis and the Concept of Operations. It also gives evidence of how different categories of requirements can be derived from the main tools used during the analysis. Eventually, a trade-off analysis has been conducted to determine, through the evaluation of appropriate figure of merits, which scenario could be the best one, in terms of cost-effectiveness. Future activities should improve the analysis of this study, extending it to the following areas:

- the complete design and sizing of the spacecraft's subsystems;
- the mission trajectory design;
- the development of additional documents of the Concept of Operations: End-to-end Communication Strategy, Command and Data Architecture, Operational Facilities, Integrated Logistic Support and Critical Events;
- the evaluation of the Risk Assessment.

The examination of these areas would allow a thorough definition of the mission. It would provide details of different aspects that lead a mission to fulfill its initial objectives.

# Appendix A

# Traceability of Requirements

Each requirement provided in this section is identified through a Requirement ID (Req ID), a unique denomination which contains information about the followings:

- the category to which it belongs, provided through the initials. For example "fr" stands for "functional requirement".
- the requirement from which it derives, within the same category.

When some requirements derive from an other one, within the same category, the Req IDs gives evidence of this relation in the following way: The IDs of the low-level requirements contain number from "1" to "9" in the same position where the ID of the top-level requirement had a "0". For sake of clarity, the functional requirement *fr_ 1-000-000-000* generates the requirements identified as *fr_ 1-100-000-000* and *fr_ 1-200-000-000.* Analogously, these requirements generates the requirements identified as *fr_ 1-110-000-000* and *fr_ 1-210-000-000.*

When the requirements deriving from a previous one are more than 9, the list continues as "...9-1", "...9-2" and so on.

For some categories, when the top-level requirements are more than 9, such as for the interface and the operational ones, a letter of the alphabet is indicated in the ID. Starting from "A", a sequence of 9 requirements with the same letter is shown followed by a sequence with the following letters in the alphabetic order.

## A.1 Mission and Programmatic Requirements

| REQ ID | DESCRIPTION | DEPENS ON | AFFECTS |
|---|---|---|---|
| **Mission Requirements** | | | |
| **mr_10** | The mission shall support the cis-Martian space exploration | | fr_1-000-000; fr_2-000-000; fr_3-000-000; fr_4-000-000 |
| **mr_20** | The mission shall provide transportation system between LOP-G and MOS | | fr_1-000-000; fr_2-000-000; fr_3-000-000; fr_4-000-000; pr_10 |
| **mr_30** | The mission shall sustain MOS development, evolution, operations and crew support | | pr_20; pr_40 |
| **mr_40** | The transportation system shall exploit electric propulsion | | fr_2-111-111 |
| **mr_50** | The transportation system shall transfer end-to-end unmanned payloads | | fr_1-000-000; fr_2-000-000; fr_3-000-000; fr_4-000-000; pr_50 |
| **mr_60** | ICV shall be a reusable system | | mr_61 |
| **mr_61** | ICV shall be able to perform on-orbit refueling | mr_60 | pr_30; fr_3-200-000 |
| **Programmatic Requirements** | | | |
| **pr_10** | ICV shall exploit existing infrastructures | mr_20 | pr_11 |
| **pr_20** | ICV shall support Mars Mission during all phases in mission timeframe | mr_30 | |
| **pr_30** | Existing space facilities for on-orbit refueling shall be exploited | mr_61 | |
| **pr_40** | Cargo shall be delivered within TBD months | mr_30 | |
| **pr_11** | Mating elements and rendezvous and docking interfaces shall be standardized | pr_10 | |
| **pr_50** | Unmanned operations autonomy shall be enhanced | mr_50 | |

Table A.1: Mission and Programmatic Requirements

# A.2 System of Systems Requirements

| REQ ID | DESCRIPTION | DEPENDS ON | AFFECTS |
|---|---|---|---|
| **Functional Requirements** | | | |
| **fr_1-000-000** | Launch capabilities shall be provided | mr_10; mr_50; mr_50 | fr_1-100-000; fr_1-200-000 |
| **fr_2-000-000** | Transportation shall be performed | mr_10; mr_20; mr_50 | fr_2-100-000; fr_2-200-000 |
| **fr_3-000-000** | Mission support from orbit shall be provided | mr_10; mr_20; mr_50 | fr_3-100-000; fr_3-200-000; fr_3-300-000; fr_3-400-000; fr_3-500-000; fr_3-600-000; fr_3-700-000; fr_3-800-000 |
| **fr_4-000-000** | Mission support from Earth shall be provided | mr_10; mr_20; mr_50 | fr_4-100-000; fr_4-200-000 |
| **fr_1-100-000** | Orbit insertion shall be performed | fr_1-000-000 | fr_1-110-000 |
| **fr_1-200-000** | Launch support capabilities shall be provided | fr_1-000-000 | fr_1-210-000 |
| **fr_2-100-000** | Unmanned cargo transfer between cislunar and mars environment shall be accomplished | fr_2-000-000 | fr_2-110-000 |
| **fr_2-200-000** | Cargo containing capabilities shall be furnished | fr_2-000-000 | fr_2-210-000 |
| **fr_3-100-000** | Fuel storage capabilities shall be provided | fr_3-000-000 | fr_3-110-000 |
| **fr_3-200-000** | On-orbit refuelling capabilities shall be provided | fr_3-000-000; mr_61 | fr_3-210-000 |
| **fr_3-300-000** | Communication capabilities with ground shall be provided | fr_3-000-000 | fr_3-310-000 |
| **fr_3-400-000** | Navigation capabilities from lunar orbits shall be provided | fr_3-000-000 | fr_3-410-000 |
| **fr_3-500-000** | Communication capabilities from mars orbits shall be provided | fr_3-000-000 | fr_3-510-000 |
| **fr_3-600-000** | Navigation capabilities from mars orbits shall be provided | fr_3-000-000 | fr_3-610-000 |
| **fr_3-700-000** | Habitat capabilities in cislunar orbit shall be provided | fr_3-000-000 | fr_3-710-000 |
| **fr_3-800-000** | Habitat capabilities in mars orbit shall be provided | fr_3-000-000 | fr_3-810-000 |
| **fr_4-100-000** | Mission control capabilities shall be ensured | fr_4-000-000 | fr_4-110-000 |
| **fr_4-200-000** | Mission logistic capabilities shall be ensured | fr_4-000-000 | fr_4-210-000 |

Table A.2: Functional Requirements - System of Systems

| REQ ID | DESCRIPTION | DEPENDS ON | AFFECTS |
|---|---|---|---|
| **Functional Requirements - Refinement** | | | |
| **fr_1-110-000** | Launch Vehicle shall provide ICV orbit insertion capabilities | fr_1-100-000 | |
| **fr_1-210-000** | Launch Control Station shall provide launch support capabilities | fr_1-200-000 | |
| **fr_2-110-000** | ICV shall accomplish unmanned cargo transfer between cislunar and mars environment | fr_2-100-000 | fr_2-111-000; fr_2-112-000; fr_2-113-000; fr_2-114-000; fr_2-115-000; fr_2-116-000; fr_2-117-000; fr_2-118-000; fr_2-119-1-000; fr_2-119-2-000; fr_2-119-3-000; fr_2-119-4-000; fr_2-119-5-000 |
| **fr_2-210-000** | Cargo Module shall furnish containing cargo capabilities | fr_2-200-000 | |
| **fr_3-110-000** | LOP-G shall provide fuel storage capabilities | fr_3-100-000 | |
| **fr_3-210-000** | ICV shall provide on-orbit refuelling capabilities | fr_3-200-000 | fr_3-211-000; fr_3-212-000 |
| **fr_3-310-000** | ICV shall provide communication capabilities with ground | fr_3-300-000 | fr_3-311-000; fr_3-312-000 |
| **fr_3-410-000** | Lunar Navigation Satellites shall provide navigation capabilities from lunar orbits | fr_3-400-000 | |
| **fr_3-510-000** | Mars Communication Satellites shall provide communication capabilities from mars orbits | fr_3-500-000 | |
| **fr_3-610-000** | Mars Navigation Satellites shall provide navigation capabilities from mars orbits | fr_3-600-000 | |
| **fr_3-710-000** | LOP-G shall provide habitat capabilities in cislunar orbit | fr_3-700-000 | |
| **fr_3-810-000** | MOS shall provide habitat capabilities in mars orbit | fr_3-800-000 | |
| **fr_4-110-000** | Mission Control Center shall ensure mission control capabilities | fr_4-100-000 | |
| **fr_4-210-000** | Mission Logistic Center shall ensure mission logistic capabilities | fr_4-200-000 | |
| **Configuration Requirements** | | | |
| **cr_1** | The Launch Segment shall consist of the Launch Vehicle and the Launch Control Station | | |
| **cr_2** | The Space Segment shall consist of the ICV, the Cargo Module, the LOP-G, the MOS, the Lunar Navigation Satellites, the Mars Communication Satellites and the Mars Navigation Satellites | | |
| **cr_3** | The Ground Segment shall consist of the Mission Control Center and the Mission Logistic Center | | |

Table A.3: Functional Requirements Refinement and Configuration Requirements - System of Systems

| REQ ID | DESCRIPTION | DEPENDS ON | AFFECTS |
|---|---|---|---|
| **Interface Requirements** | | | |
| **ir_A_10** | ICV shall interface with Launch Vehicle | | ir_A_11; ir_A_12 |
| **ir_A_20** | ICV shall interface with Cargo Module | | ir_A_21; ir_A_22; ir_A_23 |
| **ir_A_30** | ICV shall interface with Lunar Navigation Satellites | | ir_A_31; ir_A_32 |
| **ir_A_40** | ICV shall interface with LOP-G | | ir_A_41; ir_A_42; ir_A_43; ir_A_44 |
| **ir_A_50** | ICV shall interface with MOS | | ir_A_51; ir_A_52; ir_A_53 |
| **ir_A_60** | ICV shall interface with Mars Communication Satellites | | ir_A_61; ir_A_62 |
| **ir_A_70** | ICV shall interface with Mars Navigation Satellites | | ir_A_71; ir_A_72 |
| **ir_A_80** | ICV shall interface with Mission Control Center | | ir_A_81; ir_A_82 |
| **ir_A_90** | ICV shall interface with Mission Logistic Center | | ir_A_91; ir_A_92 |
| **ir_B_10** | Launch Vehicle shall interface with ICV | | ir_B_11; ir_B_12 |
| **ir_B_20** | Launch Vehicle shall interface with Launch Control Station | | ir_B_21; ir_B_22 |
| **ir_B_30** | Launch Control Station shall interface with Launch Vehicle | | ir_B_31; ir_B_32 |
| **ir_B_40** | Cargo Module shall interface with ICV | | ir_B_41; ir_B_42; ir_B_43 |
| **ir_B_50** | Cargo Module shall interface with LOP-G | | ir_B_51 |
| **ir_B_60** | Cargo Module shall interface with MOS | | ir_B_61 |
| **ir_B_70** | LOP-G shall interface with ICV | | ir_B_71; ir_B_72; ir_B_73; ir_B_74 |
| **ir_B_80** | LOP-G shall interface with Cargo Module | | ir_B_81 |
| **ir_B_90** | Lunar Navigation Satellites shall interface with ICV | | ir_B_91; ir_B_92 |
| **ir_C_10** | Mars Navigation Satellites shall interface with ICV | | ir_C_11; ir_C_12 |
| **ir_C_20** | MOS shall interface with ICV | | ir_C_21; ir_C_22; ir_C_23 |
| **ir_C_30** | MOS shall interface with Cargo Module | | ir_C_30 |
| **ir_C_40** | MOS shall interface with Mars Communication Satellites | | ir_C_41; ir_C_42 |
| **ir_C_50** | Mars Communication Satellites shall interface with ICV | | ir_C_51; ir_C_52 |
| **ir_C_60** | Mars Communication Satellites shall interface with MOS | | ir_C_61; ir_C_62 |
| **ir_C_70** | Mars Communication Satellites shall interface with Mission Control Center | | ir_C_71; ir_C_72 |
| **ir_C_80** | Mission Control Center shall interface with ICV | | ir_C_81; ir_C_82 |
| **ir_C_90** | Mission Control Center shall interface with Mars Communication Satellites | | ir_C_91; ir_C_92 |

Table A.4: Interface Requirements (part1) - System of Systems

| REQ ID | DESCRIPTION | DEPENDS ON | AFFECTS |
|---|---|---|---|
| **Interface Requirements** | | | |
| **ir_D_10** | Mission Control Center shall interface with Mission Logistic Center | | ir_D_11; ir_D_12 |
| **ir_D_20** | Mission Logistic Center shall interface with ICV | | ir_D_21; ir_D_22 |
| **ir_D_30** | Mission Logistic Center shall interface with Mission Control Center | | ir_D_31; ir_D_32 |
| **ir_A_11** | ICV shall be contained within Launch Vehicle | ir_A_10 | |
| **ir_A_12** | ICV shall transmit data to Launch Vehicle | ir_A_10 | |
| **ir_A_21** | ICV shall mechanically interface with Cargo Module | ir_A_20 | |
| **ir_A_22** | ICV shall supply Cargo Module with electric power | ir_A_20 | |
| **ir_A_23** | ICV shall receive data from Cargo Module | ir_A_20 | |
| **ir_A_31** | ICV shall transmit data to Lunar Navigation Satellites | ir_A_30 | |
| **ir_A_32** | ICV shall receive data from Lunar Navigation Satellites | ir_A_30 | |
| **ir_A_41** | ICV shall mechanically interface with LOP-G | ir_A_40 | |
| **ir_A_42** | ICV shall transmit data to LOP-G | ir_A_40 | |
| **ir_A_43** | ICV shall receive data from LOP-G | ir_A_40 | |
| **ir_A_44** | ICV shall be supplied with fuel by LOP-G | ir_A_40 | |
| **ir_A_51** | ICV shall mechanically interface with MOS | ir_A_50 | |
| **ir_A_52** | ICV shall transmit data to MOS | ir_A_50 | |
| **ir_A_53** | ICV shall receive data from MOS | ir_A_50 | |
| **ir_A_61** | ICV shall transmit data to Mars Communication Satellites | ir_A_60 | |
| **ir_A_62** | ICV shall receive data from Mars Communication Satellites | ir_A_60 | |
| **ir_A_71** | ICV shall transmit data to Mars Navigation Satellites | ir_A_70 | |
| **ir_A_72** | ICV shall receive data from Mars Navigation Satellites | ir_A_70 | |
| **ir_A_81** | ICV shall transmit data to Mission Control Center | ir_A_80 | |
| **ir_A_82** | ICV shall receive commands from Mission Control Center | ir_A_80 | |
| **ir_A_91** | ICV shall transmit data to Mission Logistic Center | ir_A_90 | |
| **ir_A_92** | ICV shall receive commands from Mission Logistic Center | ir_A_90 | |
| **ir_B_11** | Launch Vehicle shall mechanically interface with ICV | ir_B_10 | |
| **ir_B_12** | Launch Vehicle shall receive data from ICV | ir_B_10 | |

Table A.5: Interface Requirements (part 2) - System of Systems

| REQ ID | DESCRIPTION | DEPENDS ON | AFFECTS |
|---|---|---|---|
| **Interface Requirements** | | | |
| **ir_B_21** | Launch Vehicle shall receive data from Launch Control Station | ir_B_20 | |
| **ir_B_22** | Launch Vehicle shall transmit data to Launch Control Station | ir_B_20 | |
| **ir_B_31** | Launch Control Station shall receive data from Launch Vehicle | ir_B_30 | |
| **ir_B_32** | Launch Control Station shall transmit data to Launch Vehicle | ir_B_30 | |
| **ir_B_41** | Cargo Module shall mechanically interface with ICV | ir_B_40 | |
| **ir_B_42** | Cargo Module shall transmit data to ICV | ir_B_40 | |
| **ir_B_43** | Cargo Module shall be supplied with electric power by ICV | ir_B_40 | |
| **ir_B_51** | Cargo Module shall mechanically interface with LOP-G | ir_B_50 | |
| **ir_B_61** | Cargo Module shall mechanically interface with MOS | ir_B_60 | |
| **ir_B_71** | LOP-G shall mechanically interface with ICV | ir_B_70 | |
| **ir_B_72** | LOP-G shall receive data from ICV | ir_B_70 | |
| **ir_B_73** | LOP-G shall transmit data to ICV | ir_B_70 | |
| **ir_B_74** | LOP-G shall supply ICV with fuel | ir_B_70 | |
| **ir_B_81** | LOP-G shall mechanically interface with Cargo Module | ir_B_80 | |
| **ir_B_91** | Lunar Navigation Satellites shall receive data from ICV | ir_B_90 | |
| **ir_B_92** | Lunar Navigation Satellites shall transmit data to ICV | ir_B_90 | |
| **ir_C_11** | Mars Navigation Satellites shall receive data from ICV | ir_C_10 | |
| **ir_C_12** | Mars Navigation Satellites shall transmit data to ICV | ir_C_10 | |
| **ir_C_21** | MOS shall mechanically interface with ICV | ir_C_20 | |
| **ir_C_22** | MOS shall receive data from ICV | ir_C_20 | |
| **ir_C_23** | MOS shall transmit data to ICV | ir_C_20 | |
| **ir_C_30** | MOS shall mechanically interface with Cargo Module | ir_C_30 | |
| **ir_C_41** | MOS shall receive data from Mars Communication Satellites | ir_C_40 | |
| **ir_C_42** | MOS shall transmit data to Mars Communication Satellites | ir_C_40 | |
| **ir_C_51** | Mars Communication Satellites shall receive data from ICV | ir_C_50 | |
| **ir_C_52** | Mars Communication Satellites shall transmit data to ICV | ir_C_50 | |
| **ir_C_61** | Mars Communication Satellites shall receive data from MOS | ir_C_60 | |

Table A.6: Interface Requirements (part 3) - System of Systems

| REQ ID | DESCRIPTION | DEPENDS ON | AFFECTS |
|---|---|---|---|
| **Interface Requirements** | | | |
| **ir_C_62** | Mars Communication Satellites shall transmit data to MOS | ir_C_60 | |
| **ir_C_71** | Mars Communication Satellites shall receive data from Mission Control Center | ir_C_70 | |
| **ir_C_72** | Mars Communication Satellites shall transmit data to Mission Control Center | ir_C_70 | |
| **ir_C_81** | Mission Control Center shall receive data from ICV | ir_C_80 | |
| **ir_C_82** | Mission Control Center shall transmit commands to ICV | ir_C_80 | |
| **ir_C_91** | Mission Control Center shall receive data from Mars Communication Satellites | ir_C_90 | |
| **ir_C_92** | Mission Control Center shall transmit data to Mars Communication Satellites | ir_C_90 | |
| **ir_D_11** | Mission Control Center shall receive data from Mission Logistic Center | ir_D_10 | |
| **ir_D_12** | Mission Control Center shall transmit data to Mission Logistic Center | ir_D_10 | |
| **ir_D_21** | Mission Logistic Center shall receive data from ICV | ir_D_20 | |
| **ir_D_22** | Mission Logistic Center shall transmit commands to ICV | ir_D_20 | |
| **ir_D_31** | Mission Logistic Center shall receive data from Mission Control Center | ir_D_30 | |
| **ir_D_32** | Mission Logistic Center shall transmit data to Mission Control Center | ir_D_30 | |

Table A.7: Interface Requirements (part 4) - System of Systems

## A.3 System Requirements

| REQ ID | DESCRIPTION | DEPENDS ON | AFFECTS |
|---|---|---|---|
| **Functional Requirements** | | | |
| **fr_2-111-000** | ICV shall provide spacecraft propulsion | fr_2-110-000 | fr_2-111-100 |
| **fr_2-112-000** | ICV shall provide propellant management capabilities | fr_2-110-000 | fr_2-112-100 |
| **fr_2-113-000** | ICV shall provide navigation capabilities | fr_2-110-000 | fr_2-113-100 |
| **fr_2-114-000** | ICV shall provide guidance capabilities | fr_2-110-000 | fr_2-114-100 |
| **fr_2-115-000** | ICV shall provide control capabilities | fr_2-110-000 | fr_2-115-100 |
| **fr_2-116-000** | ICV shall provide power management capabilities | fr_2-110-000 | fr_2-116-100 |
| **fr_2-117-000** | ICV shall provide thermal control capabilities | fr_2-110-000 | fr_2-117-100 |
| **fr_2-118-000** | ICV shall provide environmental protection capabilities | fr_2-110-000 | fr_2-118-100 |
| **fr_2-119-1-000** | ICV shall provide data handling capabilities | fr_2-110-000 | fr_2-119-1-100 |
| **fr_2-119-2-000** | ICV shall provide electronic inputs distribution | fr_2-110-000 | fr_2-119-2-100 |
| **fr_2-119-3-000** | ICV shall provide structural integrity | fr_2-110-000 | fr_2-119-3-100 |
| **fr_2-119-4-000** | ICV shall provide structural support capabilities | fr_2-110-000 | fr_2-119-4-100 |
| **fr_2-119-5-000** | ICV shall provide data communication with orbit elements | fr_2-110-000 | fr_2-119-5-100 |
| **fr_3-311-000** | ICV shall receive data from ground | fr_3-310-000 | fr_3-311-100 |
| **fr_3-312-000** | ICV shall transmit data to ground | fr_3-310-000 | fr_3-312-100 |
| **fr_3-211-000** | ICV shall provide structural support to on-orbit refueling | fr_3-210-000 | fr_3-211-100 |
| **fr_3-212-000** | ICV shall provide fluidic support to on-orbit refueling | fr_3-210-000 | fr_3-212-100 |

Table A.8: Functional Requirements - System

| REQ ID | DESCRIPTION | DEPENDS ON | AFFECTS |
|---|---|---|---|
| **Functional Requirements - Refinement** | | | |
| **fr_2-111-100** | PROP shall provide spacecraft propulsion | fr_2-111-000 | fr_2-111-120 |
| **fr_2-112-100** | PROP shall provide propellant management capabilities | fr_2-112-000 | fr_2-112-110; fr_2-112-120 |
| **fr_2-113-100** | AOCS shall provide navigation capabilities | fr_2-113-000 | fr_2-113-110; fr_2-113-120; fr_2-113-130; fr_2-113-140 |
| **fr_2-114-100** | AOCS shall provide guidance capabilities | fr_2-114-000 | fr_2-114-110; fr_2-114-120; fr_2-114-130 |
| **fr_2-115-100** | AOCS shall provide control capabilities | fr_2-115-000 | fr_2-115-110; fr_2-115-120; fr_2-115-130; fr_2-115-140 |
| **fr_2-116-100** | EPS shall provide power management capabilities | fr_2-116-000 | fr_2-116-110; fr_2-116-120; fr_2-116-130; fr_2-116-140 |
| **fr_2-117-100** | TCS shall provide thermal control capabilities | fr_2-117-000 | fr_2-117-110; fr_2-117-120; fr_2-117-130; fr_2-117-140; fr_2-117-150; fr_2-117-160; fr_2-117-170 |
| **fr_2-118-100** | S&M shall provide environmental protection capabilities | fr_2-118-000 | fr_2-118-110; fr_2-118-120 |
| **fr_2-119-1-100** | DMS shall provide data handling capabilities | fr_2-119-1-000 | fr_2-119-1-110; fr_2-119-1-120; fr_2-119-1-130; fr_2-119-1-140; fr_2-119-1-150; fr_2-119-1-160; fr_2-119-1-170; fr_2-119-1-180; fr_2-119-1-190; fr_2-119-1-190-1 |
| **fr_2-119-2-100** | HARN shall provide electronic inputs distribution | fr_2-119-2-000 | fr_2-119-2-110; fr_2-119-2-120; fr_2-119-2-130 |
| **fr_2-119-3-100** | S&M shall provide structural integrity | fr_2-119-3-000 | fr_2-119-3-110; fr_2-119-3-120; fr_2-119-3-130 |
| **fr_2-119-4-100** | S&M shall provide structural support capabilities | fr_2-119-4-000 | fr_2-119-4-110; fr_2-119-4-120; fr_2-119-4-130 |
| **fr_2-119-5-100** | TT&C shall provide data communication with orbit elements | fr_2-119-5-000 | fr_2-119-5-110; fr_2-119-5-120; fr_2-119-5-130; fr_2-119-5-140; fr_2-119-5-160 |
| **fr_3-311-100** | TT&C shall receive data from ground | fr_3-311-000 | fr_3-311-110; fr_3-311-120; fr_3-311-130 |
| **fr_3-312-100** | TT&C shall transmit data to ground | fr_3-312-000 | fr_3-312-110; fr_3-312-120; fr_3-312-130; fr_3-312-140; fr_3-312-150 |
| **fr_3-211-100** | REF shall provide structural support to on-orbit refueling | fr_3-211-000 | fr_3-211-110 |
| **fr_3-212-100** | REF shall provide fluidic support to on-orbit refueling | fr_3-212-000 | fr_3-211-110; fr_3-212-110; fr_3-212-120; fr_3-212-130; fr_3-212-140 |
| **Configuration Requirements** | | | |
| **cr_4** | The ICV shall consist of PROP, AOCS, EPS, DMS, TT&C, TCS, S&M, REF and HARN | | |

Table A.9: Functional Requirements Refinement and Configuration Requirements - System

| REQ ID | DESCRIPTION | DEPENDS ON | AFFECTS |
|---|---|---|---|
| **Interface Requirements** | | | |
| **ir_E_10** | EPS shall interface with AOCS | | ir_E_11 |
| **ir_E_20** | EPS shall interface with TCS | | ir_E_21 |
| **ir_E_30** | EPS shall interface with PROP | | ir_E_31 |
| **ir_E_40** | EPS shall interface with REF | | ir_E_41 |
| **ir_E_50** | EPS shall interface with TT&C | | ir_E_51 |
| **ir_E_60** | EPS shall interface with DMS | | ir_E_61; ir_E_62; ir_E_63 |
| **ir_E_70** | EPS shall interface with S&M | | ir_E_71 |
| **ir_E_80** | EPS shall interface with HARN | | ir_E_81; ir_E_82 |
| **ir_E_90** | AOCS shall interface with EPS | | ir_E_91 |
| **ir_F_10** | AOCS shall interface with DMS | | ir_F_11; ir_F_12 |
| **ir_F_20** | AOCS shall interface with S&M | | ir_F_21 |
| **ir_F_30** | AOCS shall interface with HARN | | ir_F_31; ir_F_32; ir_F_33 |
| **ir_F_40** | TCS shall interface with EPS | | ir_F_41 |
| **ir_F_50** | TCS shall interface with DMS | | ir_F_51; ir_F_52 |
| **ir_F_60** | TCS shall interface with S&M | | ir_F_61 |
| **ir_F_70** | TCS shall interface with HARN | | ir_F_71; ir_F_72; ir_F_73 |
| **ir_F_80** | PROP shall interface with EPS | | ir_F_81 |
| **ir_F_90** | PROP shall interface with REF | | ir_F_91 |
| **ir_G_10** | PROP shall interface with DMS | | ir_G_11; ir_G_12 |
| **ir_G_20** | PROP shall interface with S&M | | ir_G_21 |
| **ir_G_30** | PROP shall interface with HARN | | ir_G_31; ir_G_32; ir_G_33 |
| **ir_G_40** | REF shall interface with EPS | | ir_G_41 |
| **ir_G_50** | REF shall interface with PROP | | ir_G_51; ir_G_52 |
| **ir_G_60** | REF shall interface with DMS | | ir_G_61 |
| **ir_G_70** | REF shall interface with S&M | | ir_G_71 |
| **ir_G_80** | REF shall interface with HARN | | ir_G_81; ir_G_82; ir_G_83 |
| **ir_G_90** | TT&C shall interface with EPS | | ir_G_91 |
| **ir_H_10** | TT&C shall interface with DMS | | ir_H_11; ir_H_12 |
| **ir_H_20** | TT&C shall interface with S&M | | ir_H_21 |
| **ir_H_30** | TT&C shall interface with HARN | | ir_H_31; ir_H_32; ir_H_33 |
| **ir_H_40** | DMS shall interface with AOCS | | ir_H_41; ir_H_42 |
| **ir_H_50** | DMS shall interface with TCS | | ir_H_51; ir_H_52 |
| **ir_H_60** | DMS shall interface with PROP | | ir_H_61; ir_H_62 |
| **ir_H_70** | DMS shall interface with REF | | ir_H_71; ir_H_72 |
| **ir_H_80** | DMS shall interface with EPS | | ir_H_81; ir_H_82; ir_H_83 |
| **ir_H_90** | DMS shall interface with TT&C | | ir_H_91; ir_H_92 |

Table A.10: Interface Requirements (part 1) - System

| REQ ID | DESCRIPTION | DEPENDS ON | AFFECTS |
|---|---|---|---|
| **Interface Requirements** | | | |
| **ir_I_10** | DMS shall interface with S&M | | ir_I_11 |
| **ir_I_20** | DMS shall interface with HARN | | ir_I_21; ir_I_22; ir_I_23; ir_I_24; ir_I_25 |
| **ir_I_30** | S&M shall interface with AOCS | | ir_I_31 |
| **ir_I_40** | S&M shall interface with TCS | | ir_I_41 |
| **ir_I_50** | S&M shall interface with PROP | | ir_I_51 |
| **ir_I_60** | S&M shall interface with REF | | ir_I_61 |
| **ir_I_70** | S&M shall interface with EPS | | ir_I_71 |
| **ir_I_80** | S&M shall interface with TT&C | | ir_I_81 |
| **ir_I_90** | S&M shall interface with DMS | | ir_I_91 |
| **ir_J_10** | S&M shall interface with HARN | | ir_J_11 |
| **ir_J_20** | HARN shall interface with AOCS | | ir_J_21; ir_J_22; ir_J_23 |
| **ir_J_30** | HARN shall interface with TCS | | ir_J_31; ir_J_32; ir_J_33 |
| **ir_J_40** | HARN shall interface with PROP | | ir_J_41; ir_J_42; ir_J_43 |
| **ir_J_50** | HARN shall interface with REF | | ir_J_51; ir_J_52; ir_J_53 |
| **ir_J_60** | HARN shall interface with EPS | | ir_J_61; ir_J_62 |
| **ir_J_70** | HARN shall interface with TT&C | | ir_J_71; ir_J_72 |
| **ir_J_80** | HARN shall interface with DMS | | ir_J_81; ir_J_82 |
| **ir_J_90** | HARN shall interface with S&M | | ir_J_91 |
| **ir_E_11** | EPS shall provide electric power to AOCS | ir_E_10 | |
| **ir_E_21** | EPS shall provide electric power to TCS | ir_E_20 | |
| **ir_E_31** | EPS shall provide electric power to PROP | ir_E_30 | |
| **ir_E_41** | EPS shall provide electric power to REF | ir_E_40 | |
| **ir_E_51** | EPS shall provide electric power to TT&C | ir_E_50 | |
| **ir_E_61** | EPS shall provide electric power to DMS | ir_E_60 | |
| **ir_E_62** | EPS shall transmit telemetry and housekeeping data to DMS | ir_E_60 | |
| **ir_E_63** | EPS shall receive command data from DMS | ir_E_60 | |
| **ir_E_71** | EPS shall be structurally supported by S&M | ir_E_70 | |
| **ir_E_81** | EPS shall be provided with commands through HARN | ir_E_80 | |
| **ir_E_82** | EPS shall transmit telemetry through HARN | ir_E_80 | |
| **ir_E_91** | AOCS shall be supplied with electrical power by EPS | ir_E_90 | |
| **ir_F_11** | AOCS shall transmit telemetry and housekeeping data to DMS | ir_F_10 | |
| **ir_F_12** | AOCS shall receive command data from DMS | ir_F_10 | |
| **ir_F_21** | AOCS shall be structurally supported by S&M | ir_F_20 | |
| **ir_F_31** | AOCS shall be provided with commands through HARN | ir_F_30 | |
| **ir_F_32** | AOCS shall transmit telemetry through HARN | ir_F_30 | |
| **ir_F_33** | AOCS shall be provided with electrical power through HARN | ir_F_30 | |

Table A.11: Interface Requirements (part 2) - System

| REQ ID | DESCRIPTION | DEPENDS ON | AFFECTS |
|---|---|---|---|
| **Interface Requirements** | | | |
| **ir_F_41** | TCS shall be supplied with electrical power by EPS | ir_F_40 | |
| **ir_F_51** | TCS shall transmit telemetry and housekeeping data to DMS | ir_F_50 | |
| **ir_F_52** | TCS shall receive command data from DMS | ir_F_50 | |
| **ir_F_61** | TCS shall be structurally supported by S&M | ir_F_60 | |
| **ir_F_71** | TCS shall be provided with commands through HARN | ir_F_70 | |
| **ir_F_72** | TCS shall transmit telemetry through HARN | ir_F_70 | |
| **ir_F_73** | TCS shall be provided with electrical power through HARN | ir_F_70 | |
| **ir_F_81** | PROP shall be supplied with electrical power by EPS | ir_F_80 | |
| **ir_F_91** | PROP shall be supplied with fuel by REF | ir_F_90 | |
| **ir_G_11** | PROP shall transmit telemetry and housekeeping data to DMS | ir_G_10 | |
| **ir_G_12** | PROP shall receive command data from DMS | ir_G_10 | |
| **ir_G_21** | PROP shall be structurally supported by S&M | ir_G_20 | |
| **ir_G_31** | PROP shall be provided with commands through HARN | ir_G_30 | |
| **ir_G_32** | PROP shall transmit telemetry through HARN | ir_G_30 | |
| **ir_G_33** | PROP shall be provided with electrical power through HARN | ir_G_30 | |
| **ir_G_41** | REF shall be supplied with electrical power by EPS | ir_G_40 | |
| **ir_G_51** | REF shall supply PROP with fuel | ir_G_50 | |
| **ir_G_52** | REF shall transmit telemetry and housekeeping data to DMS | ir_G_60 | |
| **ir_G_61** | REF shall receive command data from DMS | ir_G_60 | |
| **ir_G_71** | REF shall be structurally supported by S&M | ir_G_70 | |
| **ir_G_81** | REF shall be provided with commands through HARN | ir_G_80 | |
| **ir_G_82** | REF shall transmit telemetry through HARN | ir_G_80 | |
| **ir_G_83** | REF shall be provided with electrical power through HARN | ir_G_80 | |
| **ir_G_91** | TT&C shall be supplied with electrical power by EPS | ir_G_90 | |
| **ir_H_11** | TT&C shall transmit command data to DMS | ir_H_10 | |
| **ir_H_12** | TT&C shall receive telemetry and housekeeping data from DMS | ir_H_10 | |
| **ir_H_21** | TT&C shall be structurally supported by S&M | ir_H_20 | |
| **ir_H_31** | TT&C shall be provided with telemetry through HARN | ir_H_30 | |
| **ir_H_32** | TT&C shall transmit commands through HARN | ir_H_30 | |
| **ir_H_33** | TT&C shall be provided with electrical power through HARN | ir_H_30 | |

Table A.12: Interface Requirements (part 3) - System

| REQ ID | DESCRIPTION | DEPENDS ON | AFFECTS |
|---|---|---|---|
| **Interface Requirements** | | | |
| **ir_H_81** | DMS shall be supplied with electrical power by EPS | ir_H_80 | |
| **ir_H_91** | DMS shall transmit telemetry and housekeeping data to TT&C | ir_H_90 | |
| **ir_H_92** | DMS shall receive command data from TT&C | ir_H_90 | |
| **ir_I_11** | DMS shall be structurally supported by S&M | ir_I_10 | |
| **ir_H_41** | DMS shall receive telemetry and housekeeping data from AOCS | ir_H_40 | |
| **ir_H_51** | DMS shall receive telemetry and housekeeping data from TCS | ir_H_50 | |
| **ir_H_61** | DMS shall receive telemetry and housekeeping data from PROP | ir_H_60 | |
| **ir_H_71** | DMS shall receive telemetry and housekeeping data from REF | ir_H_70 | |
| **ir_H_82** | DMS shall receive telemetry and housekeeping data from EPS | ir_H_80 | |
| **ir_H_42** | DMS shall transmit command data to AOCS | ir_H_40 | |
| **ir_H_52** | DMS shall transmit command data to TCS | ir_H_50 | |
| **ir_H_62** | DMS shall transmit command data to PROP | ir_H_60 | |
| **ir_H_72** | DMS shall transmit command data to REF | ir_H_70 | |
| **ir_H_83** | DMS shall transmit command data to EPS | ir_H_80 | |
| **ir_I_21** | DMS shall be provided with commands through HARN | ir_I_20 | |
| **ir_I_22** | DMS shall transmit telemetry through HARN | ir_I_20 | |
| **ir_I_23** | DMS shall gather telemetry and housekeeping data through HARN | ir_I_20 | |
| **ir_I_24** | DMS shall distribute commands through HARN | ir_I_20 | |
| **ir_I_25** | DMS shall be provided with electrical power through HARN | ir_I_20 | |
| **ir_I_31** | S&M shall structurally support AOCS | ir_I_30 | |
| **ir_I_41** | S&M shall structurally support TCS | ir_I_40 | |
| **ir_I_51** | S&M shall structurally support PROP | ir_I_50 | |
| **ir_I_61** | S&M shall structurally support REF | ir_I_60 | |
| **ir_I_71** | S&M shall structurally support EPS | ir_I_70 | |
| **ir_I_81** | S&M shall structurally support DMS | ir_I_80 | |
| **ir_I_91** | S&M shall structurally support TT&C | ir_I_90 | |
| **ir_J_11** | S&M shall structurally support HARN | ir_J_10 | |
| **ir_J_91** | HARN shall be structurally supported by S&M | ir_J_90 | |
| **ir_J_21** | HARN shall transmit commands from DMS to AOCS | ir_J_20 | |
| **ir_J_31** | HARN shall transmit commands from DMS to TCS | ir_J_30 | |

Table A.13: Interface Requirements (part 4) - System

| REQ ID | DESCRIPTION | DEPENDS ON | AFFECTS |
|---|---|---|---|
| **Interface Requirements** | | | |
| **ir_J_41** | HARN shall transmit commands from DMS to PROP | ir_J_40 | |
| **ir_J_51** | HARN shall transmit commands from DMS to REF | ir_J_50 | |
| **ir_J_61** | HARN shall transmit commands from DMS to EPS | ir_J_60 | |
| **ir_J_71** | HARN shall transmit commands from TT&C to DMS | ir_J_70 | |
| **ir_J_81** | HARN shall transmit telemetry and housekeeping data from DMS to TT&C | ir_J_80 | |
| **ir_J_22** | HARN shall transmit telemetry and housekeeping data from AOCS to DMS | ir_J_20 | |
| **ir_J_32** | HARN shall transmit telemetry and housekeeping data from TCS to DMS | ir_J_30 | |
| **ir_J_42** | HARN shall transmit telemetry and housekeeping data from PROP to DMS | ir_J_40 | |
| **ir_J_52** | HARN shall transmit telemetry and housekeeping data from REF to DMS | ir_J_50 | |
| **ir_J_62** | HARN shall transmit telemetry and housekeeping data from EPS to DMS | ir_J_60 | |
| **ir_J_23** | HARN shall conduct electric power from EPS to AOCS | ir_J_20 | |
| **ir_J_33** | HARN shall conduct electric power from EPS to TCS | ir_J_30 | |
| **ir_J_43** | HARN shall conduct electric power from EPS to PROP | ir_J_40 | |
| **ir_J_53** | HARN shall conduct electric power from EPS to REF | ir_J_50 | |
| **ir_J_72** | HARN shall conduct electric power from EPS to TT&C | ir_J_70 | |
| **ir_J_82** | HARN shall conduct electric power from EPS to DMS | ir_J_80 | |

Table A.14: Interface Requirements (part 5) - System

| REQ ID | DESCRIPTION | DEPENDS ON | AFFECTS |
|---|---|---|---|
| **Performance Requirements** | | | |
| **per-PROP_10** | PROP shall provide TBD Ns of total impulse | fr_2-111-100 | |
| **per-PROP_20** | PROP shall provide TBD N of thrust level | fr_2-111-100 | |
| **per-PROP_30** | PROP shall manage TBD kg of propellants | fr_2-112-100 | |
| **per-AOCS_10** | AOCS shall provide solar arrays and antennas pointing | fr_2-115-100 | |
| **per-AOCS_20** | AOCS shall provide TBD° of control accuracy | fr_2-115-100 | |
| **per-AOCS_30** | AOCS shall provide TBD rad/s speed of response | fr_2-115-100 | |
| **per-AOCS_40** | AOCS shall provide TBD Nm of torque capability | fr_2-115-100 | |
| **per-AOCS_50** | AOCS shall counteract TBD Nm disturbance torques | fr_2-115-100 | |
| **per-EPS_10** | EPS shall provide power to operate the equipment in compliance with power requirements for each mission phase | fr_2-116-100 | |
| **per-EPS_20** | EPS shall provide protection against short circuits and fault isolations | fr_2-116-100 | |
| **per-TCS_10** | TCS shall maintain equipment within operative temperatures | fr_2-117-100 | |
| **per-TCS_20** | TCS shall cope with the thermal needs of the ICV subsystems as required at any mission phase | fr_2-117-100 | |
| **per-TCS_30** | TCS shall cope with the space environment throughout the mission | fr_2-117-100 | |
| **per-TT&C_10** | TT&C shall receive data at a rate of TBD bit/s from orbit elements | fr_2-119-5-100 | |
| **per-TT&C_20** | TT&C shall transmit data at a rate of TBD bit/s to orbit elements | fr_2-119-5-100 | |
| **per-TT&C_30** | TT&C shall detect signal from orbit elements within TBD allowable error rate | fr_2-119-5-100 | |
| **per-TT&C_40** | TT&C shall receive data at a rate of TBD bit/s from ground | fr_3-311-100 | |
| **per-TT&C_50** | TT&C shall downlink data at a rate of TBD bit/s | fr_3-312-100 | |
| **per-TT&C_60** | TT&C shall detect signal from ground within TBD allowable error rate | fr_3-311-100 | |
| **per-TT&C_70** | TT&C shall operate within TBD frequency range | fr_2-119-5-100; fr_3-311-100; fr_3-312-100 | |

Table A.15: Performance Requirements (part 1) - System

| REQ ID | DESCRIPTION | DEPENDS ON | AFFECTS |
|---|---|---|---|
| **Performance Requirements** | | | |
| **per-DMS_10** | DMS shall cope with data transfer and storage requirements of the ICV subsystems at any mission phase | fr_2-119-1-100 | |
| **per-DMS_20** | DMS shall transmit data at rates that supports command and telemetry requirements at any mission phase | fr_2-119-1-100 | |
| **per-HARN_10** | HARN shall dissipate power not exceeding TBD % of operating power | fr_2-119-2-100 | |
| **per-HARN_20** | HARN shall be compliant with voltage drop requirements | fr_2-119-2-100 | |
| **per-HARN_30** | HARN shall ensure compatibility for communication to devices onboard the ICV | fr_2-119-2-100 | |
| **per-S&M_10** | S&M shall be able to withstand a maximum axial load factor of TBD g and a maximum lateral load factor of TBD g | fr_2-119-3-100 | |
| **per-S&M_20** | S&M shall guarantee fundamental frequencies of the S/C within the requirements of the Launch Vehicle to avoid dynamic coupling | fr_2-119-3-100 | |
| **per-S&M_30** | S&M shall support the mechanical static and dynamic loads encountered during ICV entire lifetime, including: ground operations, launch, deployment and on-orbit operations. | fr_2-119-3-100 | |
| **per-S&M_40** | S&M shall be able to survive ground, launch and on-orbit environments | fr_2-118-100 | |
| **per-S&M_50** | S&M shall cope with components physical and interface requirements | fr_2-119-4-100 | |
| **per-S&M_60** | S&M shall cope with components requirements for rigidity and thermoelastic distorsion | fr_2-119-4-100 | |
| **per-REF_10** | REF shall be able to afford a maximum force of TBD N and a maximum torque of TBD Nm | fr_3-211-100 | |
| **per-REF_20** | REF shall ensure sealing between the ICV and the LOP-G refueling port | fr_3-211-100 | |
| **per-REF_30** | REF shall ensure correct couplings between the ICV and the LOP-G refueling port | fr_3-212-100 | |

Table A.16: Performance Requirements (part 2) - System

## A.4 Subsystems Requirements

| REQ ID | DESCRIPTION | DEPENDS ON | AFFECTS |
|---|---|---|---|
| **Functional Requirements** | | | |
| **fr_2-111-110** | PROP shall provide electric power conditioning and control | fr_2-111-100 | fr_2-111-112 |
| **fr_2-111-120** | PROP shall provide thrust | fr_2-111-100 | fr_2-111-112 |
| **fr_2-112-110** | PROP shall store propellant | fr_2-112-100 | fr_2-112-111 |
| **fr_2-112-120** | PROP shall distribute propellant | fr_2-112-100 | fr_2-112-121 |
| **fr_2-113-110** | AOCS shall provide data for orbit determination | fr_2-113-100 | fr_2-113-111 |
| **fr_2-113-120** | AOCS shall provide data for attitude determination | fr_2-113-100 | fr_2-113-121 |
| **fr_2-113-130** | AOCS shall provide orbit determination | fr_2-113-100 | fr_2-113-131 |
| **fr_2-113-140** | AOCS shall provide attitude determination | fr_2-113-100 | fr_2-113-141 |
| **fr_2-114-110** | AOCS shall provide orbit propagation | fr_2-114-100 | fr_2-114-111 |
| **fr_2-114-120** | AOCS shall provide reference attitude determination | fr_2-114-100 | fr_2-114-121 |
| **fr_2-114-130** | AOCS shall determinate reference trajectory and velocity profile | fr_2-114-100 | fr_2-114-131 |
| **fr_2-115-110** | AOCS shall control position | fr_2-115-100 | fr_2-115-111 |
| **fr_2-115-120** | AOCS shall control velocity | fr_2-115-100 | fr_2-115-121 |
| **fr_2-115-130** | AOCS shall control attitude | fr_2-115-100 | fr_2-115-131 |
| **fr_2-115-140** | AOCS shall control angular rate | fr_2-115-100 | fr_2-115-141 |
| **fr_2-116-110** | EPS shall generate power | fr_2-116-100 | fr_2-116-111 |
| **fr_2-116-120** | EPS shall store energy | fr_2-116-100 | fr_2-116-121 |
| **fr_2-116-130** | EPS shall distribute power | fr_2-116-100 | fr_2-116-131 |
| **fr_2-116-140** | EPS shall regulate power | fr_2-116-100 | fr_2-116-141 |
| **fr_2-117-110** | TCS shall collect heat | fr_2-117-100 | fr_2-117-111 |
| **fr_2-117-120** | TCS shall transport heat | fr_2-117-100 | fr_2-117-121 |
| **fr_2-117-130** | TCS shall provide thermal insulation | fr_2-117-100 | fr_2-117-131 |
| **fr_2-117-140** | TCS shall provide heat rejection | fr_2-117-100 | fr_2-117-141 |
| **fr_2-117-150** | TCS shall provide local heat sink | fr_2-117-100 | fr_2-117-151 |
| **fr_2-117-160** | TCS shall manage thermal control | fr_2-117-100 | fr_2-117-161 |
| **fr_2-117-170** | TCS shall monitor temperatures | fr_2-117-100 | fr_2-117-171 |

Table A.17: Functional Requirements (part 1) - Subsystems

| REQ ID | DESCRIPTION | DEPENDS ON | AFFECTS |
|---|---|---|---|
| **Functional Requirements** | | | |
| **fr_2-118-110** | S&M shall provide radiation protection | fr_2-118-100 | fr_2-118-111 |
| **fr_2-118-120** | S&M shall provide MMOD protection | fr_2-118-100 | fr_2-118-121 |
| **fr_2-119-3-110** | S&M shall carry ground handling loads | fr_2-119-3-100 | fr_2-119-3-111 |
| **fr_2-119-3-120** | S&M shall carry launch loads | fr_2-119-3-100 | fr_2-119-3-121 |
| **fr_2-119-3-130** | S&M shall carry operational loads | fr_2-119-3-100 | fr_2-119-3-131 |
| **fr_2-119-4-110** | S&M shall provide structural support for components | fr_2-119-4-100 | fr_2-119-4-111 |
| **fr_2-119-4-120** | S&M shall provide structural support for mating operations | fr_2-119-4-100 | fr_2-119-4-121 |
| **fr_2-119-4-130** | S&M shall provide structural support for grasping | fr_2-119-4-100 | fr_2-119-4-131 |
| **fr_3-211-110** | REF shall provide mechanical alignment | fr_3-211-100 | fr_3-211-111 |
| **fr_3-212-110** | REF shall provide fluid coupling | fr_3-212-100 | fr_3-212-111 |
| **fr_3-212-120** | REF shall provide electrical coupling | fr_3-212-100 | fr_3-212-121 |
| **fr_3-212-130** | REF shall transfer propellant | fr_3-212-100 | fr_3-212-131 |
| **fr_3-212-140** | REF shall provide storage for received propellant | fr_3-212-100 | fr_3-212-141 |
| **fr_2-119-1-110** | DMS shall receive commands | fr_2-119-1-100 | fr_2-119-1-111 |
| **fr_2-119-1-120** | DMS shall validate commands | fr_2-119-1-100 | fr_2-119-1-121 |
| **fr_2-119-1-130** | DMS shall process commands | fr_2-119-1-100 | fr_2-119-1-131 |
| **fr_2-119-1-140** | DMS shall store commands | fr_2-119-1-100 | fr_2-119-1-141 |
| **fr_2-119-1-150** | DMS shall distribute commands | fr_2-119-1-100 | fr_2-119-1-151 |
| **fr_2-119-1-160** | DMS shall collect telemetries | fr_2-119-1-100 | fr_2-119-1-161 |
| **fr_2-119-1-170** | DMS shall process telemetries | fr_2-119-1-100 | fr_2-119-1-171 |
| **fr_2-119-1-180** | DMS shall store telemetries | fr_2-119-1-100 | fr_2-119-1-181 |
| **fr_2-119-1-190** | DMS shall process mission data | fr_2-119-1-100 | fr_2-119-1-191 |
| **fr_2-119-1-190-1** | DMS shall store mission data | fr_2-119-1-100 | fr_2-119-1-191-1 |
| **fr_2-119-5-110** | TT&C shall provide pointing for receiving | fr_2-119-5-100 | fr_2-119-5-111 |
| **fr_2-119-5-120** | TT&C shall receive data from orbit elements | fr_2-119-5-100 | fr_2-119-5-121 |
| **fr_2-119-5-130** | TT&C shall elaborate data received from orbit elements | fr_2-119-5-100 | fr_2-119-5-131 |
| **fr_2-119-5-140** | TT&C shall elaborate data to be transmitted to orbit elements | fr_2-119-5-100 | fr_2-119-5-141 |

Table A.18: Functional Requirements (part 2) - Subsystems

| REQ ID | DESCRIPTION | DEPENDS ON | AFFECTS |
|---|---|---|---|
| **Functional Requirements** | | | |
| **fr_2-119-5-150** | TT&C shall provide pointing for transmitting | fr_2-119-5-100 | fr_2-119-5-151 |
| **fr_2-119-5-160** | TT&C shall transmit data to orbit elements | fr_2-119-5-100 | fr_2-119-5-161 |
| **fr_3-311-110** | TT&C shall provide pointing for receiving from ground | fr_3-311-100 | fr_3_311-111 |
| **fr_3-311-120** | TT&C shall receive commands from ground | fr_3-311-100 | fr_3_311-121 |
| **fr_3-311-130** | TT&C shall elaborate commands | fr_3-311-100 | fr_3_311-131 |
| **fr_3-312-110** | TT&C shall provide pointing for transmitting to ground | fr_3-312-100 | fr_3_312-111 |
| **fr_3-312-120** | TT&C shall elaborate telemetries to be transmitted | fr_3-312-100 | fr_3_312-121 |
| **fr_3-312-130** | TT&C shall transmit telemetries | fr_3-312-100 | fr_3_312-131 |
| **fr_3-312-140** | TT&C shall elaborate mission data to be transmitted | fr_3-312-100 | fr_3_312-141 |
| **fr_3-312-150** | TT&C shall transmit mission data | fr_3-312-100 | fr_3_312-151 |
| **fr_2-119-2-110** | HARN shall distribute electric power | fr_2-119-2-100 | fr_2_119-2-111 |
| **fr_2-119-2-120** | HARN shall distribute command data | fr_2-119-2-100 | fr_2_119-2-121 |
| **fr_2-119-2-130** | HARN shall distribute telemetries | fr_2-119-2-100 | fr_2_119-2-131 |

Table A.19: Functional Requirements (part 3) - Subsystems

| REQ ID | DESCRIPTION | DEPENDS ON | AFFECTS |
|---|---|---|---|
| **Functional Requirements - Refinement** | | | |
| **fr_2-111-111** | PPU shall provide electric power conditioning and control | fr_2-111-110 | |
| **fr_2-111-112** | Thruster Units shall provide thrust | fr_2-111-120 | |
| **fr_2-112-111** | Fuel tanks shall store propellant | fr_2-112-110 | |
| **fr_2-112-121** | Feeding system shall distribute propellant | fr_2-112-120 | |
| **fr_2-113-111** | Orbit sensors shall provide data for orbit determination | fr_2-113-110 | |
| **fr_2-113-121** | Attitude sensors shall provide data for attitude determination | fr_2-113-120 | |
| **fr_2-113-131** | AOCS OBC shall provide orbit determination | fr_2-113-130 | |
| **fr_2-113-141** | AOCS OBC shall provide attitude determination | fr_2-113-140 | |
| **fr_2-114-111** | AOCS OBC shall provide orbit propagation | fr_2-114-110 | |
| **fr_2-114-121** | AOCS OBC shall provide reference attitude determination | fr_2-114-120 | |
| **fr_2-114-131** | AOCS OBC shall determinate reference trajectory and velocity profile | fr_2-114-130 | |
| **fr_2-115-111** | AOCS actuators shall control position | fr_2-115-110 | |
| **fr_2-115-121** | AOCS actuators shall control velocity | fr_2-115-120 | |

Table A.20: Functional Requirements Refinement (part 1) - Subsystems

| REQ ID | DESCRIPTION | DEPENDS ON | AFFECTS |
|---|---|---|---|
| **Functional Requirements - Refinement** | | | |
| **fr_2-116-111** | Solar arrays shall generate power | fr_2-116-110 | |
| **fr_2-116-121** | Batteries shall store energy | fr_2-116-120 | |
| **fr_2-116-131** | PCDU shall distribute power | fr_2-116-130 | |
| **fr_2-116-141** | PCDU shall regulate power | fr_2-116-140 | |
| **fr_2-117-111** | Heat pipes shall collect heat | fr_2-117-110 | |
| **fr_2-117-121** | Heat pipes shall transport heat | fr_2-117-120 | |
| **fr_2-117-131** | MLI blankets shall provide thermal insulation | fr_2-117-130 | |
| **fr_2-117-141** | Radiators shall provide heat rejection | fr_2-117-140 | |
| **fr_2-117-151** | Electrical heaters shall provide local heat sink | fr_2-117-150 | |
| **fr_2-117-161** | TCS OBC shall manage thermal control | fr_2-117-160 | |
| **fr_2-117-171** | Temperature sensors shall monitor temperatures | fr_2-117-170 | |
| **fr_2-118-111** | Radiation shields shall provide radiation protection | fr_2-118-110 | |
| **fr_2-118-121** | MDPS panels shall provide MMOD protection | fr_2-118-120 | |
| **fr_2-119-3-111** | Primary structure shall carry ground handling loads | fr_2-119-3-110 | |
| **fr_2-119-3-121** | Primary structure shall carry launch loads | fr_2-119-3-120 | |
| **fr_2-119-3-131** | Primary structure shall carry operational loads | fr_2-119-3-130 | |
| **fr_2-119-4-111** | Secondary structure shall provide structural support for components | fr_2-119-4-110 | |
| **fr_2-119-4-121** | Docking I/F shall provide structural support for mating operations | fr_2-119-4-120 | |
| **fr_2-119-4-131** | Grasping I/F shall provide structural support for grasping | fr_2-119-4-130 | |
| **fr_3-211-111** | Fluid Plane shall provide mechanical alignment | fr_3-211-110 | |
| **fr_3-212-111** | Fluid couplings shall provide fluid coupling | fr_3-212-110 | |
| **fr_3-212-121** | Electrical connector shall provide electrical coupling | fr_3-212-120 | |
| **fr_3-212-131** | Refueling valves shall transfer propellant | fr_3-212-130 | |
| **fr_3-212-141** | Refueling tanks shall provide storage for received propellant | fr_3-212-140 | |
| **fr_2-119-1-111** | Commands decoder shall receive commands | fr_2-119-1-110 | |
| **fr_2-119-1-121** | Commands decoder shall validate commands | fr_2-119-1-120 | |
| **fr_2-119-1-131** | OBC shall process commands | fr_2-119-1-130 | |
| **fr_2-119-1-141** | Data Storage Unit shall store commands | fr_2-119-1-140 | |
| **fr_2-119-1-151** | RIU shall distribute commands | fr_2-119-1-150 | |
| **fr_2-119-1-161** | RIU shall collect telemetries | fr_2-119-1-160 | |

Table A.21: Functional Requirements Refinement (part 2) - Subsystems

| REQ ID | DESCRIPTION | DEPENDS ON | AFFECTS |
|---|---|---|---|
| **Functional Requirements - Refinement** | | | |
| **fr_2-119-1-171** | OBC shall process telemetries | fr_2-119-1-170 | |
| **fr_2-119-1-181** | Data Storage Unit shall store telemetries | fr_2-119-1-180 | |
| **fr_2-119-1-191** | OBC shall process mission data | fr_2-119-1-190 | |
| **fr_2-119-1-191-1** | Data Storage Unit shall store mission data | fr_2-119-1-190-1 | |
| **fr_2-119-5-111** | Auto-tracking equipment shall provide pointing for receiving | fr_2-119-5-110 | |
| **fr_2-119-5-121** | Antennas shall receive data from orbit elements | fr_2-119-5-120 | |
| **fr_2-119-5-131** | Receiver shall elaborate data received from orbit elements | fr_2-119-5-130 | |
| **fr_2-119-5-141** | Transmitter shall elaborate data to be transmitted to orbit elements | fr_2-119-5-140 | |
| **fr_2-119-5-151** | Auto-tracking equipment shall provide pointing for transmitting | fr_2-119-5-150 | |
| **fr_2-119-5-161** | Antennas shall transmit data to orbit elements | fr_2-119-5-160 | |
| **fr_3_311-111** | Auto-tracking equipment shall provide pointing for receiving from ground | fr_3-311-110 | |
| **fr_3_311-121** | Antennas shall receive commands from ground | fr_3-311-120 | |
| **fr_3_311-131** | Receiver shall elaborate commands | fr_3-311-130 | |
| **fr_3_312-111** | Auto-tracking equipment shall provide pointing for transmitting to ground | fr_3-312-110 | |
| **fr_3_312-121** | Transmitter shall elaborate telemetries to be transmitted | fr_3-312-120 | |
| **fr_3_312-131** | Antennas shall transmit telemetries | fr_3-312-130 | |
| **fr_3_312-141** | Transmitter shall elaborate mission data to be transmitted | fr_3-312-140 | |
| **fr_3_312-151** | Antennas shall transmit mission data | fr_3-312-150 | |
| **fr_2_119-2-111** | Electric power harness shall distribute electric power | fr_2-119-2-110 | |
| **fr_2_119-2-121** | Data bus shall distribute command data | fr_2-119-2-120 | |
| **fr_2_119-2-131** | Data bus shall distribute telemetries | fr_2-119-2-130 | |

Table A.22: Functional Requirements Refinement (part 3) - Subsystems

| REQ ID | DESCRIPTION | DEPENDS ON | AFFECTS |
|---|---|---|---|
| **Configuration Requirements** | | | |
| **cr_5** | The PROP shall consist of PPU, Thruster Units, fuel tanks and feeding system | | |
| **cr_6** | The AOCS shall consist of orbit sensors, attitude sensors, AOCS actuators and AOCS OBC | | |
| **cr_7** | The EPS shall consist of solar arrays, batteries and PCDU | | |
| **cr_8** | The TCS shall consist of heat pipes, MLI blankets, radiators, electrical heaters, TCS OBC, and temperature sensors | | |
| **cr_9** | The S&M shall consist of radiation shields, MDPS panels, primary structure, secondary structure, docking I/F and grasping I/F | | |
| **cr_10** | The REF shall consist of Fluid Plane, fluid couplings, electrical connector, refueling valves and refueling tanks | | |
| **cr_11** | The DMS shall consist of commands decoder, OBC, Data Storage Unit and RIU | | |
| **cr_12** | The TT&C shall consist of antennas, receiver, transmitter and auto-tracking equipment | | |
| **cr_13** | The HARN shall consist of data bus and electric power harness | | |

Table A.23: Configuration Requirements - Subsystems

# A.5 Environmental and Operational Requirements

## A.5.1 Scenario 1A

| REQ ID | DESCRIPTION |
|---|---|
| **Environmental Requirements** | |
| **Launch** | |
| **er-LAUNCH_10** | ICV shall withstand launch environment during launch |
| **er-LAUNCH_20** | ICV shall be able to sustain launch loads during launch |
| **er-LAUNCH_30** | ICV shall be able to sustain launch vibration during launch |
| **er-LAUNCH_40** | ICV shall limit heat leak/gain to/from natural environment during launch |
| **er-LAUNCH_50** | ICV shall withstand TBD temperature range during launch |
| **er-LAUNCH_60** | ICV shall be able to sustain separation shock during launch |
| **Early Operations** | |
| **er-EO_10** | ICV shall withstand LEO environment during early operations |
| **er-EO_20** | ICV shall be able to sustain operational loads during early operations |
| **er-EO_30** | ICV shall limit heat leak/gain to/from natural environment during early operations |
| **er-EO_40** | ICV shall be able to operate within TBD temperature range during early operations |
| **er-EO_50** | ICV shall withstand neutral atmosphere bombardment during early operations |
| **er-EO_60** | ICV shall withstand atmosphere particles contamination during early operations |
| **er-EO_70** | ICV shall limit charge particles effect on equipment during early operations |
| **er-EO_80** | ICV shall be able to sustain a TBD radiation dose during early operations |
| **er-EO_90** | ICV shall be compliant with a TBD probability of potential damage from micrometeroids and orbital debris impact during early operations |
| **EOR to LOP-G** | |
| **er-EOR1_10** | ICV shall withstand EOR environment during EOR from LEO to LOP-G |
| **er-EOR1_20** | ICV shall be able to sustain operational loads during EOR from LEO to LOP-G |
| **er-EOR1_30** | ICV shall limit heat leak/gain to/from natural environment during EOR from LEO to LOP-G |
| **er-EOR1_40** | ICV shall be able to operate within TBD temperature range during EOR from LEO to LOP-G |
| **er-EOR1_50** | ICV shall be able to sustain a TBD radiation dose during EOR from LEO to LOP-G |
| **er-EOR1_60** | ICV shall limit radiation effect on equipment during EOR from LEO to LOP-G |
| **er-EOR1_70** | ICV shall be compliant with a TBD probability of potential damage from micrometeroids and orbital debris during EOR from LEO to LOP-G |
| **er-EOR1_80** | ICV shall be compatible with TBD amount of plume impingement from thrusters during EOR from LEO to LOP-G |
| **Rendezvous and docking to LOP-G refueling port** | |
| **er-R&D-LOP-G1_10** | ICV shall be compliant with the LOP-G docking mechanism of the refueling port |
| **er-R&D-LOP-G1_20** | ICV shall limit loads during docking to the LOP-G refueling port |
| **er-R&D-LOP-G1_30** | ICV shall absorb shocks during docking to the LOP-G refueling port |
| **er-R&D-LOP-G1_40** | ICV shall be able to compensate TBD misalignments with the LOP-G refueling port |
| **er-R&D-LOP-G1_50** | ICV shall not exceed TBD contact velocity while docking to the LOP-G refueling port |

Table A.24: Environmental Requirements (part 1) - Scenario 1A

| REQ ID | DESCRIPTION |
|---|---|
| **Environmental Requirements** | |
| **Refueling** | |
| **er-REF_10** | ICV shall be compliant with the LOP-G refueling system |
| **er-REF_20** | ICV shall sustain fuel pressure during refueling phase |
| **er-REF_30** | ICV shall limit torques and forces during refueling phase |
| **Berthing and undocking (from LOP-G refueling port)** | |
| **er-BER&UNDOCK1_10** | ICV shall be compliant with the capture mechanism of the LOP-G robotic arm |
| **er-BER&UNDOCK1_20** | ICV shall limit loads during berthing and undocking from the LOP-G refueling port |
| **er-BER&UNDOCK1_30** | ICV shall absorb shocks during berthing and undocking from the LOP-G refueling port |
| **Relocation to Cargo Module** | |
| **er-RELOC1_10** | ICV shall be able to sustain robotic arm loads during relocation to Cargo Module |
| **Docking and release (to Cargo Module)** | |
| **er-DOCK&REL1_10** | ICV shall be compliant with the Cargo Module docking mechanism |
| **er-DOCK&REL1_20** | ICV shall limit loads during docking and release to Cargo Module |
| **er-DOCK&REL1_30** | ICV shall absorb shocks during docking and release to Cargo Module |
| **Undocking from LOP-G** | |
| **er-UNDOCK-LOP-G_10** | ICV shall limit loads while undocking the Cargo Module from LOP-G |
| **er-UNDOCK-LOP-G_20** | ICV shall absorb shocks while undocking the Cargo Module from LOP-G |
| **er-UNDOCK-LOP-G_30** | ICV shall maintain TBD separation velocity while undocking the Cargo Module from LOP-G |
| **LOP-G-MOS EOR** | |
| **er-EOR2_10** | ICV shall withstand EOR environment during EOR from LOP-G to MOS |
| **er-EOR2_20** | ICV shall be able to sustain operational loads during EOR from LOP-G to MOS |
| **er-EOR2_30** | ICV shall limit heat leak/gain to/from natural environment during EOR from LOP-G to MOS |
| **er-EOR2_40** | ICV shall be able to operate within TBD temperature range during EOR from LOP-G to MOS |
| **er-EOR2_50** | ICV shall be able to sustain a TBD radiation dose during EOR from LOP-G to MOS |
| **er-EOR2_60** | ICV shall limit radiation effect on equipment during EOR from LOP-G to MOS |
| **er-EOR2_70** | ICV shall be compliant with a TBD probability of potential damage from micrometeroids and orbital debris during EOR from LOP-G to MOS |
| **er-EOR2_80** | ICV shall be compatible with TBD amount of plume impingement from thrusters during EOR from LOP-G to MOS |
| **Rendezvous and docking with MOS** | |
| **er-R&D-MOS_10** | ICV shall limit loads while docking the Cargo Module to the MOS docking port |
| **er-R&D-MOS_20** | ICV shall absorb shocks while docking the Cargo Module to the MOS docking port |
| **er-R&D-MOS_30** | ICV shall not exceed TBD contact velocity while docking the Cargo Module to the MOS docking port |
| **Checking and Cargo handling at MOS** | |
| **er-C&CH_10** | ICV shall maintain attitude while Cargo Module is docked at MOS |
| **er-C&CH_20** | ICV shall limit torques and forces while Cargo Module is docked at MOS |
| **Undocking from MOS** | |
| **er-UNDOCK-MOS_10** | ICV shall limit loads while undocking the Cargo Module from MOS |
| **er-UNDOCK-MOS_20** | ICV shall absorb shocks while undocking the Cargo Module from MOS |
| **er-UNDOCK-MOS_30** | ICV shall maintain TBD separation velocity while undocking the Cargo Module from MOS |

Table A.25: Environmental Requirements (part 2) - Scenario 1A

| REQ ID | DESCRIPTION |
|---|---|
| **Environmental Requirements** | |
| **MOS-LOP-G EOR** | |
| **er-EOR3_10** | ICV shall withstand EOR environment during EOR from MOS to LOP-G |
| **er-EOR3_20** | ICV shall be able to sustain operational loads during EOR from MOS to LOP-G |
| **er-EOR3_30** | ICV shall limit heat leak/gain to/from natural environment during EOR from MOS to LOP-G |
| **er-EOR3_40** | ICV shall be able to operate within TBD temperature range during EOR from MOS to LOP-G |
| **er-EOR3_50** | ICV shall be able to sustain a TBD radiation dose during EOR from MOS to LOP-G |
| **er-EOR3_60** | ICV shall limit radiation effect on equipment during EOR from MOS to LOP-G |
| **er-EOR3_70** | ICV shall be compliant with a TBD probability of potential damage from micrometeroids and orbital debris during EOR from MOS to LOP-G |
| **er-EOR3_80** | ICV shall be compatible with TBD amount of plume impingement from thrusters during EOR from MOS to LOP-G |
| **Rendezvous and docking with LOP-G** | |
| **er-R&D-LOP-G2_10** | ICV shall limit loads while docking the Cargo Module to the LOP-G docking port |
| **er-R&D-LOP-G2_20** | ICV shall absorb shocks while docking the Cargo Module to the LOP-G docking port |
| **er-R&D-LOP-G2_30** | ICV shall not exceed TBD contact velocity while docking the Cargo Module to the LOP-G docking port |
| **Logistics, checking and maintenance** | |
| **er-LCM_10** | ICV shall maintain attitude while Cargo Module is docked at LOP-G |
| **er-LCM_20** | ICV shall limit torques and forces while Cargo Module is docked at LOP-G |
| **Berthing and undocking (from Cargo Module)** | |
| **er-BER&UNDOCK2_10** | ICV shall limit loads during berthing and undocking from Cargo Module |
| **er-BER&UNDOCK2_20** | ICV shall absorb shocks during berthing and undocking from Cargo Module |
| **Relocation to LOP-G refueling port** | |
| **er-RELOC2_10** | ICV shall be able to sustain robotic arm loads during relocation to refueling port |
| **Docking and release (to LOP-G refueling port)** | |
| **er-DOCK&REL2_10** | ICV shall limit loads during docking and release to the LOP-G refueling port |
| **er-DOCK&REL2_20** | ICV shall absorb shocks during docking and release to the LOP-G refueling port |

Table A.26: Environmental Requirements (part 3) - Scenario 1A

| REQ ID | DESCRIPTION |
|---|---|
| **Operational Requirements** | |
| **or_A_10** | The ICV shall be able to enter in Launch-off mode in the Launch phase |
| **or_A_20** | The ICV shall be able to enter in Early Operations mode in the Early Operations phase |
| **or_A_30** | The ICV shall be able to enter in EP mode in the "EOR to LOP-G" phase |
| **or_A_40** | The ICV shall be able to enter in CP mode in the " Rendezvous and docking at the LOP-G refueling docking port" phase |
| **or_A_50** | The ICV shall be able to enter in Refueling mode in the Refueling phase |
| **or_A_60** | The ICV shall be able to enter in Stand-by mode in the "Berthing and undocking (at LOP-G refueling docking port)" phase |
| **or_A_70** | The ICV shall be able to enter in Stand-by mode in the "Relocation to Cargo Module" phase |
| **or_A_80** | The ICV shall be able to enter in Stand-by mode in the "Docking and release (at Cargo Module)" phase |
| **or_A_90** | The ICV shall be able to enter in CP mode in the "Undocking from LOP-G" phase |
| **or_B_10** | The ICV shall be able to enter in EP mode in the "LOP-G – MOS EOR" phase |
| **or_B_20** | The ICV shall be able to enter in CP mode in the " Rendezvous and docking with MOS" phase |
| **or_B_30** | The ICV shall be able to enter in Stand-by mode in the "Checking and Cargo handling at MOS" phase |
| **or_B_40** | The ICV shall be able to enter in Check mode in the "Checking and Cargo handling at MOS" phase |
| **or_B_50** | The ICV shall be able to enter in CP mode in the "Undocking from MOS" phase |
| **or_B_60** | The ICV shall be able to enter in EP mode in the "MOS - LOP-G EOR" phase |
| **or_B_70** | The ICV shall be able to enter in CP mode in the "Rendezvous and docking with LOP-G" phase |
| **or_B_80** | The ICV shall be able to enter in Check mode in the "Logistics, checking and maintenance" phase |
| **or_B_90** | The ICV shall be able to enter in Stand-by mode in the "Berthing and undocking (at Cargo Module)" phase |
| **or_C_10** | The ICV shall be able to enter in Stand-by mode in the "Relocation to LOP-G refueling docking port" phase |
| **or_C_20** | The ICV shall be able to enter in Stand-by mode in the "Docking and release (at LOP-G refueling docking port)" phase |
| **or_C_30** | The ICV shall be able to enter in CP mode in the "Undocking from Cargo Module" phase |
| **or_C_40** | The ICV shall be able to enter in Disposal mode in the "EOR to graveyard orbit and switch-off" phase |

Table A.27: Operational Requirements - Scenario 1A

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