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MONARCH: DESIGNING MARS' FIRST METEOROLOGICAL OBSERVATION NETWORK FOR FUTURE HUMAN EXPLORATION

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1. Abstract

In recent history, missions directed towards Mars have gained an always increasing importance among the interplanetary context: planned missions for the near future aspire to achieve plenty of groundbreaking milestones and promising technological advancements. While non-manned missions are the focus at present time, human presence on the red planet is the ultimate long-term goal; to be ready for this objective, a detailed climate predictive model, based on meteorologically focused missions, is of paramount importance. The MONARCH (Mars Observing Network for Atmospheric Research and CHaracterization) study explores the feasibility of a 5-years long Mars exploration network mission, aimed at describing atmospheric aspects, landing site characteristics, safety-related environmental aspects, and climatological risks, to build an effective and reliable weather and climate forecasting model, following MEPAG (Mars Exploration Program Analysis Group) guidelines [16] for Martian climate. The study begins with an environmental study, along with a literature review of current and past Mars-related projects; interplanetary environment and planetary characteristics are assessed, to evaluate their impact on the mission plan and architecture, but also on the future human presence. Successively, starting from a given a set of payloads for meteorological and climate planetary observation, this study explores the rating of possible landing sites for the surface segment of the network, with a final selection based on science return and human-favorability; for the orbital segment, instead, a nominal orbit is fully established and described, as final target of the mission analysis, with the perturbations expected and the corrective maneuvers planned along the lifetime of the vehicle. Operations, requirements, and phases of the mission are presented, along with an exhaustive trade-off between possible vehicles network architectures. A final framework is then selected and evaluated in depth: each vehicle is sized in all its subsystems, with an insight into the motivations and margins adopted, and a final risk analysis and general planning of the mission. The feasibility of the MONARCH mission is confirmed, with a well margined architecture and intrinsic versatility. The science return is fixed as a driver of the mission, and by following the proposed outline of the mission, it's entirely possible to build satisfying meteorological observing network, for the Martian weather study and forecast.

Keywords: Mars Exploration, Meteorological Mission, MEPAG, Feasibility Study, Distributed Spacecraft Network

2. Background

2.1. Martian Environment

Operating a Mars mission involves significant challenges due to the space and Martian environments. The absence of a magnetic field on Mars exposes the spacecraft to intense radiation from solar events and galactic cosmic rays, requiring robust shielding and radiation-hardened components even for landers. Moreover, the planet experiences extreme temperature variations, averaging -58°C, which require advanced thermal control systems. The Martian atmosphere, though thin and primarily composed of carbon dioxide, presents hazards like reactive atomic oxygen at high altitudes, which can erode spacecraft surfaces. Mars also experiences low atmospheric pressure, and frequent dust storms, which vary in size and can last from minutes to months, affecting mission operations. For example, dust storms exacerbates the Entry, Descent, and Landing (EDL) phase by absorbing solar radiation and heating the atmosphere, thus further reducing its density.

2.2. Past Martian Missions

Mars exploration missions have evolved significantly since the early 1960s, with a variety of objectives ranging from studying the planet's climate to searching for signs of life. Early missions like Mars Global Surveyor, Mars Odyssey, and Mars Express primarily focused on climate studies, offering limited insights into meteorology. Recent missions, such as the Emirates Mars Mission (Hope), have shifted towards a detailed examination of Martian weather, recognizing meteorology as a critical step for future human exploration—a priority highlighted by the Mars Exploration Program Analysis Group (MEPAG).
Common strategies across these missions reveal several recurring themes:

- Architectures: Missions typically employ either orbiter-only configurations or more complex systems that include landers and rovers. Some orbiters also serve as carriers for landers, which may be fixed platforms or mobile rovers. For example, Mars Reconnaissance Orbiter is an orbiter-only mission, while Mars Science Laboratory included the Curiosity rover delivered via a cruise stage that also functioned as an orbiter.
- Mission Procedures: Launch windows to Mars open every 26 months due to planetary alignment. After launch, spacecraft may enter a parking orbit before proceeding to Mars. Upon arrival, a Mars Orbit Insertion (MOI) maneuver places the spacecraft into an initial high, elliptical orbit. Orbiters may then use thrusters or aerobraking to achieve their operational orbits—a method first used by Mars Global Surveyor. Entry, Descent, and Landing (EDL) phases are critical and challenging due to Mars' thin atmosphere and higher gravity compared to other bodies like the Moon. Various EDL strategies include direct atmospheric entry from a hyperbolic trajectory or entry from orbit after aerobraking, utilizing heat shields, parachutes, and innovative landing systems like airbag cushioning or sky cranes.
- Power Systems: Solar panels are commonly used during the interplanetary cruise and orbital operations. However, dust accumulation on solar panels poses a significant challenge for surface missions. To mitigate this, missions like Mars Science Laboratory and Mars 2020 have employed Radioisotope Thermoelectric Generators (RTGs) to provide a consistent power supply for rovers like Curiosity and Perseverance.
- Autonomy Levels: Due to communication delays ranging from 3 to 22 minutes between Earth and Mars, missions require a high degree of autonomy, especially during critical phases like EDL. Spacecraft are equipped with onboard systems capable of executing time-tagged commands, performing self-checks, and entering safe modes autonomously. Rovers like Curiosity and Perseverance have advanced autonomous navigation systems to

create 3D models of their surroundings and avoid hazards without real-time input from Earth.

- Failures and Lessons Learned: Analyzing past mission failures has been essential for improving future mission designs. Common issues have included software errors, unit conversion mistakes (as with Mars Climate Orbiter), unintended safe-mode activations, and mechanical wear (like the wheel damage on Curiosity). These experiences have underscored the importance of rigorous testing, redundancy in critical systems, and the ability to update software remotely. Additionally, the losses of Mars Polar Lander and Beagle 2 highlighted the necessity of maintaining continuous radio coverage during the EDL phase to increase the likelihood of mission success and the ability to learn from anomalies.

By examining these recurring strategies and learning from past successes and failures, future missions can be better equipped to achieve their objectives, particularly those related to supporting human exploration of Mars through improved understanding of its meteorology and climate.

3. Mission Overview

3.1. Objectives & Requirements

The *MONARCH* mission aims at the following scientific objectives:

- Determine the aspects of the atmospheric state that affect capture and Entry, Descent and landing for human scale mission to Mars.
- Assess Landing Site characteristics and environment related to safe landing for human scale landers.
- Assess the climatological risk of dust storm activity in the human exploration zone at least one year in advance of landing operations.

It is clear that both an Orbital Segment and a Land Segment are necessary to achieve those high level goals; indeed, the high level mission requirements can be summarized as follows:

- For 5 years, characterize from orbit:
  - The 3D wind profile up to the 80 km with resolution < 5 km;
  - The vertical temperature profile up to 80 km;
  - The dust transportation up to 80 km;
  - The dust storms and clouds distribution and evolution.
- For 2 years, characterize from surface:
  - The 3D wind field, temperature and meteorological parameters and dust transportation;
  - The seismic activity in the Landing Site.
- Launch date shall be $>$2029

3.2. Objectives & Requirements

To achieve these objectives, the mission is shaped around a given ensemble of payloads and instruments, which cover all the needed monitoring activities and are the starting point of the whole design.

For the ground segment:

- Meteorology package, with a wide set of sensors for temperature, wind, pressure, humidity, solar flux and dust impacts.
- Meteorological LIDAR
- Doppler Radio Science instrument
- 3-axis seismometer
- Stereo panoramic camera
- Deployable heat flow and physical properties package

While for the orbit segment:

- Sub-mm sounder
- Wide angle camera
- Thermal IR radiometer
- Wind LIDAR
- Narrow angle camera

3.3. Architecture Trade-Off

The preliminary architecture options for the MONARCH mission consider various configurations to achieve optimal scientific return while managing mission constraints such as mass, power, and complexity. A distributed spacecraft network is required in any case due to the fact that, in order to create an accu-

rate and reliable climate model, an adequate spatial resolution is mandatory. Key options cover a multitude of spacecrafts: single and multiple orbiters at different altitudes, landers, rovers, hoppers, and helicopters, each with its pros and cons. The Analytic Hierarchy Process (AHP) was used to evaluate these options based on criteria like scientific return, reliability, and complexity.
The final rundown of six best overall solutions, involved different vehicle assemblies, with different instrument packages combinations. The most promising architectures identified were the so-called Option number 3, which includes one low-altitude orbiter, two landers, and two rovers, and Option number 4, which replaces the rovers with hoppers. After comparing these options, Option 3 was preferred due to the higher reliability of rovers over hoppers, which are still in the early stages of development and testing. Rovers provide enhanced reliability and sufficient mobility, enabling them to achieve the mission's scientific objectives, including the continuous mapping of the prescribed monitored area.

3.4. Selected Architecture

The chosen architecture for this mission thus comprises six main spacecrafts: one Orbiter, one Cruise Stage, two Landers and two Rovers.

	Size [m]	Dry Mass [kg]	Wet Mass [kg]
Orbiter	2.3×2.2×2.7	803.58	2031.58
Cruise	3.3×3.3×1.2	237.11	668.00
Lander	2.5×2.1×1.0	444.71	554.21
Rover	1.3×1.7×1.1	267.91	267.91

Table 1: Modules physical characteristics [1]

3.5. Launch Vehicle

The selected launcher is the Ariane 64 in Dual Launch configuration with the 20 m fairing, which injects the two segments (Orbiter + 1^{st} Entry Capsule and Cruise Stage + 2^{nd} Entry Capsule) directly into the interplanetary trajectory. The launch vehicle can provide the required characteristic energy of $C_3 = 9.81\ km^2/s^2$.

	Diameter [m]	Height [m]
Ext. Fairing	5.4	20
Int.Fairing	4.9	8.8

Table 2: Ariane 6: Dual Launch System fairings

3.6. Timeline & Main Events

In Fig.1 is depicted the evolution of each one of the aforementioned segments, from Launch to Disposal, with emphasis of their main maneuvers and events. After the Launch and Early Orbit Phase (LEOP), the two segments separate and begins the Interplanetary Phase, with one Entry Capsule being powered by the Orbiter, while the Cruise Stage—equipped with a circular solar array—provides power to the other Entry Capsule.
Upon reaching Mars' Sphere of Influence, both of these segments will start the Orbit Insertion Phase. After 21 days of aerobraking, the Orbiter will then reach its operative orbit and the capsules will begin the Entry Descent and Landing phase under the Earth visibility coverage, with parachute deployment and landing using retrorockets on Phlegra Dorsa.
Finally, upon successful landing, the Ground Scientific Phase can start. The Landers will deploy the ramps, allowing the Rovers to descend. Once the Rovers have reached a target distance of 60 km from each other, they will begin continuous data acquisition.
If conditions will allow it, the mission can be extended, before disposing the vehicles according to COSPAR's policy.

4. Mission Design

4.1. Landing Site selection

The candidate Landing Site is chosen among the allowed landing zones coming from the fol-

[1] For the Orbiter are reported the dimensions of the main body, with stowed solar panels

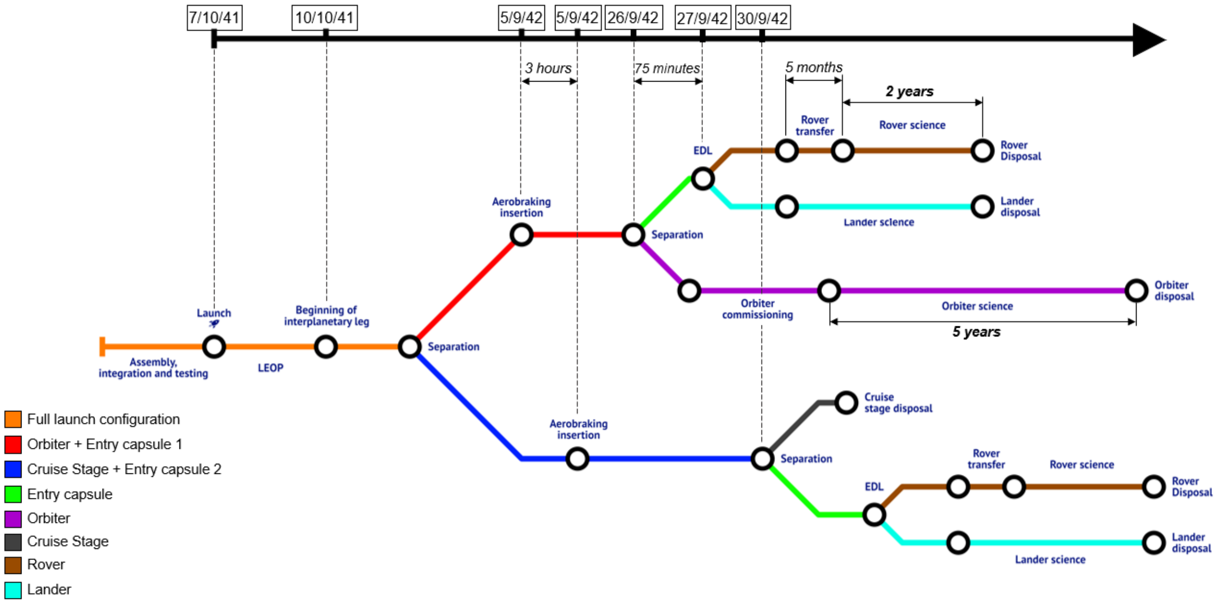

Figure 1: Timeline and main events for each segment

lowing exclusion criteria, based on the possibility to host human presence in the future [15]:

- Water accessibility [22]
- Sinking risk
- High pressure
- Severe dust storm presence

The final selection comes from some refinement criteria:

- Radiation level
- Water amount
- Morphology
- Pressure
- Human favourable condition

The selected landing site is Phlegra Dorsa (Altitude -4 km, Latitude 39°N, Longitude 172°E). A back-up site was also selected, namely the McLaughlin Crater.

4.2. Mission Analysis

A direct transfer is selected to reach Mars, since it represent a better choice with respect to a low thrust alternative in terms of ToF, electric power and propellant mass required.
The transfer window is found after evaluating all the possible opportunities in 20 years starting from 2029, considering necessary the Mars arrival without Solar conjunction, and without the occurrence of a global dust storm.

The dates selection aims for the minimum Δv, with the first impulse provided by the launcher.

Due to launcher limitations, two segments are employed and they perform similar independent trajectories, keeping a safety distance for risk mitigation. Once entered the Mars' SoI and reached the planet's atmosphere, they begin the aerobraking phase to slow down the spacecraft. The collision risk between the two segments is reduced by performing a manoeuvre with the cruise at the edges of Mars' SoI. In this way, the probes will approach the planet at a different altitude, with a 3 hours delay.

	Segment 1	**Segment 2**
h [km]	90	96

Table 3: Aerobraking insertion point altitude.

The aerobraking ellipses are planned to allow the Orbiter to insert into the operational orbit performing a coplanar manoeuvre.
The LMO is designed to obtain the highest number of passages over the Landing Site, to accumulate data in different conditions [24]. The perturbations change the orbital parameters of the operational orbit over time

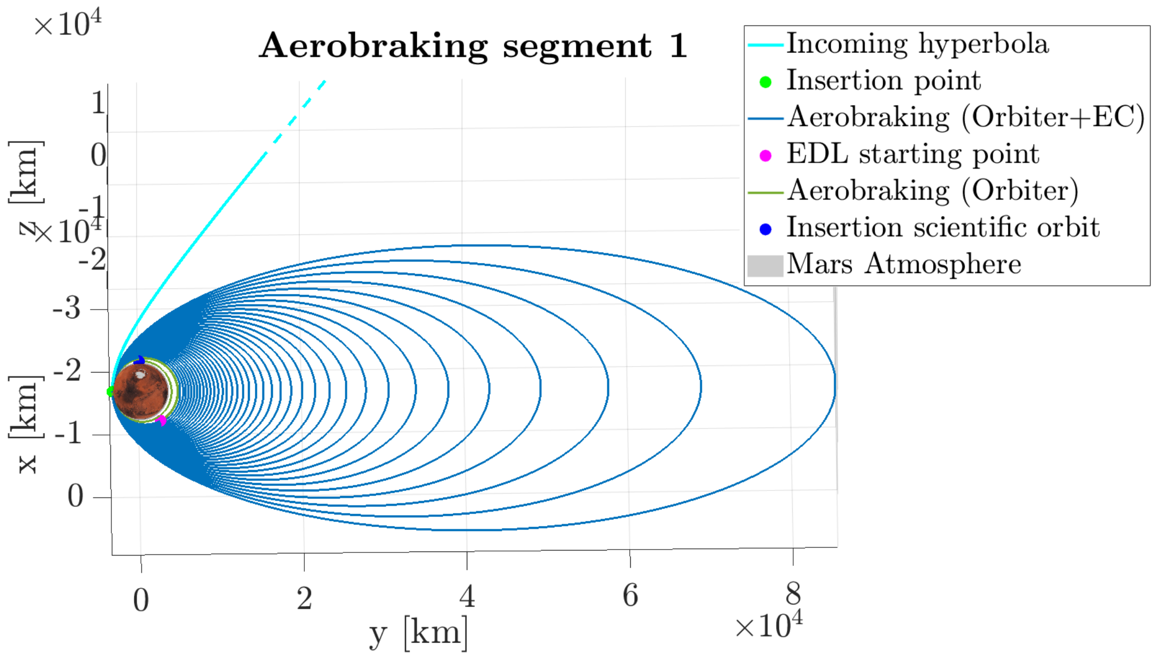

Figure 2: Aerobraking trajectory for the first segment

[3], therefore the Station Keeping activity is planned every 152 sols, to maintain the desired number of passages.
Concerning the Cruise Stage, it performs a manoeuvre after the 2^{nd} Entry Capsule landing, to be able to communicate data to Earth.

4.3. Entry, Descending and Landing

The EDL design is based on two important constraints:

- the 1^{st} Entry Capsule shall land before the Orbiter insertion into operational orbit;
- the 2^{nd} Entry Capsule shall to land after the 1^{st} Entry Capsule with a limited delay.

The EDL is performed targeting a coplanar position of the Landing Site with reference to the aerobraking orbital plane. Between the EDL alternative strategies investigated, the best option results to be the one starting during aerobraking.
The main events occurring during EDL are reported in Table 4.

Event	**Threshold**
Atmospheric entry	h = 150 km
Parachute deployment	Mach = 2.2
Heat shield detachment	Mach = 0.8
Backshell detachment	h = 2 km
Powered descent & landing	h = 1.9 km

Table 4: EDL Events [5] [17].

4.4. Propulsion System

The PS design grants control capabilities over both attitude and orbit and for all the flying vehicles. Chemical hydrazine monopropellant and $N_2H_4 - NTO$ bipropellant have been selected due to their high heritage, reliability and lower power consumption, without having an excessive increment in propellant mass; accepting the drawback of dangerous handling and cost. A first attempt in finding COTS with desired performances has been successful.
The Orbiter is equipped with 4 parallel 445N bipropellant thrusters on the aft face and with 12 monopropellant 22 N thrusters with 8 appointed to perform station-keeping activities [2]. A dual mode system pressurised with helium is responsible for propellant management and distribution. NTO has been split in two

tanks to reduce centre of gravity shifts.
The Cruise Stage has similar needs thus a similar architecture. The selected thrusters are 4 bipropellant 400 N for trajectory variations and 8 bipropellant 10 N for attitude control [4]. The helium pressurised system embeds 6 tanks to optimise the total volume of the vehicle and minimise empty spaces and CoG shifts.
The Entry Capsule is designed with 4 symmetric assemblies: each includes a 116 N monopropellant thruster for orbit control [20], a 22 N monopropellant thruster for attitude control [2] and a blowdown hydrazine-helium tank.
The Lander instead is equipped with retrorockets, preferred to a sky crane assembly because of the reduced complexity, mass and volume. To provide the high thrust required, 12 monopropellant 300 N thrusters are split in 3 clusters and canted to reduce risks of generating potential hazards for landing due to the interaction between plume and soil [2]. The propellant is delivered thanks to a blowdown system with helium by means of 3 tanks, selected to reduce the void spaces inside the Lander.

4.5. Attitude Determination and Control System

The ADCS of *MONARCH* mission is designed such that it provides the stability required for each vehicle and phase. For the Orbiter, 3-axis stabilization is adopted for all phases of the mission except the orbital maneuver sequences, where the vehicle spins around its own axis before the main/station-keeping thrusters' burn. The Orbiter is equipped with a fully redundant set of IMUs and Star Trackers to provide a continuous and precise attitude and orbit knowledge by a loosely coupled sensor fusion architecture to ensure solution redundancy. In order to survive through the harsh disturbance environment of aerobraking sequences and to provide attitude alignment, thrusters are used. For low complexity, station-keeping thrusters are also used as attitude thrusters. 4 Reaction wheels are adopted for precise pointing during the Scientific Phase and for the slew maneuvers.
A similar attitude stabilization approach and the sensor architecture is adopted for the Cruise Stage. Attitude control is performed by a suit of 8 thrusters where half is nominal and the other half is redundant.
Lastly, for the Entry Capsules, spin stabilization is adopted. 4 thrusters are used to spin-up and downspin the capsule to provide robustness against disturbances through EDL. To provide reliable attitude and altitude knowledge a redundant set of IMUs are used with a Radar Doppler Altimeter to be activated after the heat shield detachment.

4.6. Tracking, Telemetry and Telecommand

The Telemetry, Tracking, and Mission Control (TTMTC) subsystem of the *MONARCH* mission ensures seamless communication across all mission vehicles and phases. During the cruise phase, a secure link with ground stations is established through an X-band parabolic high-gain antenna, supporting high-data-rate transmissions. Additionally, an X-band patch antenna on the Cruise Stage ensures precise navigation via beam-steering capabilities, utilizing the ESTRACK deep-space tracking network.
For the Orbiter, the primary communication system uses an X-band parabolic antenna optimized for long-range transmissions, supplemented by an S-band parabolic antenna for redundancy and fault tolerance. The Orbiter also serves as a relay for surface operations, using a UHF quadrifilar helix antenna to collect scientific data from landers and rovers. This omnidirectional, circularly polarized antenna minimizes multipath interference, ensuring a robust link during visibility windows over the landing site. The separation between X-band and UHF frequencies prevents cross-interference, enhancing signal integrity during simultaneous operations. Received signals are assigned unique identifiers for clear data routing back to Earth via the Orbiter's X-band transmission system.
During the critical Entry, Descent, and Landing (EDL) phase, UHF-band data relay and tracking are managed through a wraparound UHF antenna on the Entry Capsule. Af-

ter backshell separation, signal transmission shifts to the Lander's UHF antenna, maintaining real-time telemetry until touchdown. The Lander also features an X-band high-gain antenna for redundant telemetry and telecommand links and a low-power Electra UHF Communications Terminal for proximity link communication.

To ensure data integrity, link budgets have been calculated with a Bit Error Rate (BER) of 10^{-5} for telemetry and 10^{-7} for uplink telecommands, in compliance with CCSDS standards for transmission reliability and redundancy. In accordance with ECSS-E-ST-50-05C Rev. 2 [7], separate link budgets were produced for all different parameter combinations, namely different Earth stations, different spacecraft antennas, and bit rates. Communication blackouts due to solar conjunctions have been mitigated with a solar exclusion angle of 2.3°, providing contingency plans for potential signal degradation.

Visibility windows are critical for communication efficiency. The WLIDAR instrument, which observes Mars' limbs, operates continuously, including when Mars is between the Sun and the Orbiter. However, other instruments are activated only when the landing site is visible. With a telemetry data rate of 230 kbps, the Orbiter requires a visibility window of approximately 3.52 hours to dump all data collected in one day [6]. For comparison, during the Mars Express (MEX) mission, communication ranged from 12 to 16 hours per day using two DSN stations, with individual stations visible for about 8 hours [6]. For the Lander, at a data rate of 2.048 Mbps, about 4.5 minutes of visibility is needed to transmit its daily data, while the Rover requires approximately 4.165 minutes. The Curiosity Rover, by comparison, had an 8-minute communication window [21]. Direct communication between the Lander and Earth, with a data rate of 160 bps, would take over 2000 days to dump all scientific data, making this approach unfeasible [21]. Consequently, the relay link via the Orbiter is preferred.

This robust communication design ensures high reliability and efficiency, critical to the success of the *MONARCH* mission across all phases.

4.7. On Board Data Handling

Each vehicle has its own peculiar OBDH design, with the major differences occurring between orbital and on-ground assets. In any case all of them implements the SAVOIR recommendations. The design also incorporates considerations for an E3 level of mission execution autonomy and for a fail-operational FDIR to ensure mission success despite communication delays and the harsh environment inherent in interplanetary missions.Each vehicle's OBDH subsystem is cool redundant, meaning that only the components implementing critical functions (such as high-priority telecommanding and Safeguard Memory) are hot redundant. All the main OBCs present a minimum set of boards, gathered in a backplane, comprised of:

- a CPU-board being a SBC (Single Board Computer) provided with processor, Boot Memory, Work Memory and watchdogs;
- a memory board as Platform Data Storage;
- a TM/TC-module, also called CCSDS board, comprehensive of encoder, decoder, buffers, reconfiguration unit with Safeguard Memory, and CPDU (Command Pulse Decoding Unit, for High Priority Telecommands), all integrated on the same PCB (Printed Circuit Board);
- an I/O board, connecting the OBC to external SS interfaces;
- a power board, downconverting the supply bus voltage to OBC boards working voltage.

The Orbiter features a main OBC based on a LEON3FT processor [12], plus a solid-state recorder for storing the payload data of the whole space segment and transmitting the science data through CCSDS File Delivery Protocol (CFDP). The sizing of the OBDH components for the Orbiter was performed by similarity to heritage missions, with appropriate margins applied to account for uncertainties

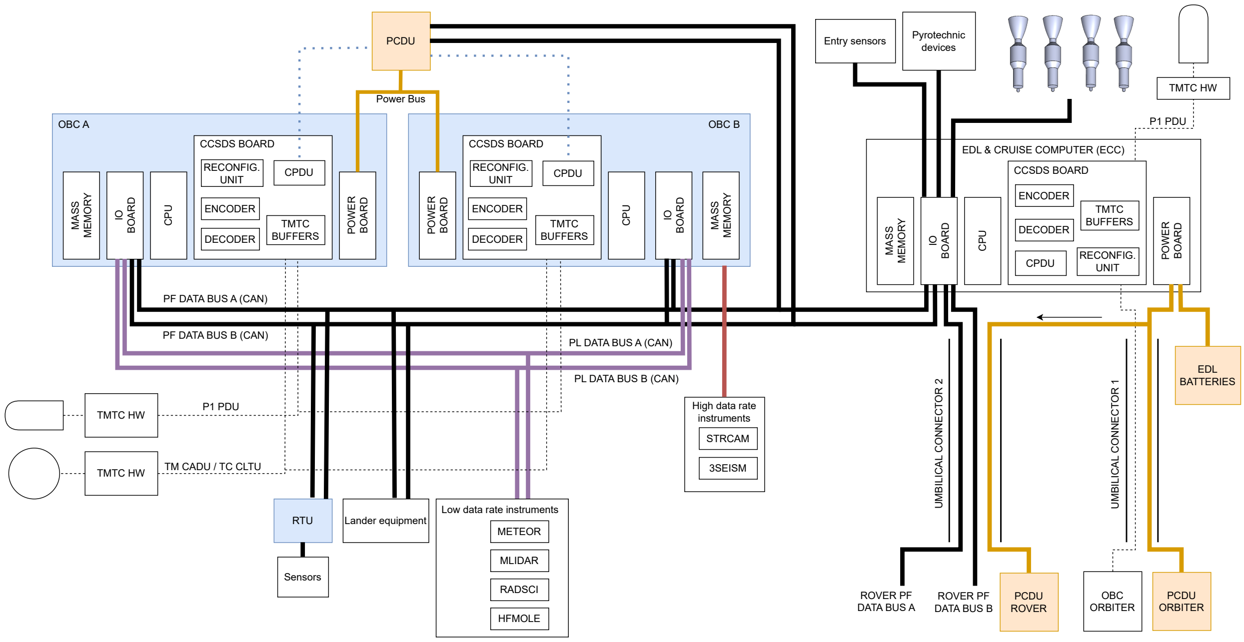

Figure 3: OBDH Subsystem Block Diagram for the Lander

in software requirements and processing demands.

The Rover instead - being tasked with Vision-Based Navigation which can require up to thousands of MIPS [19] -, in addition to the main OBC and a Rover Motor Control Assembly (for the commanding of the wheels), has a dedicated computer, enhanced by an FPGA , for image processing. Furthermore, the OBC is based on a RAD750 processor because of its greater processing power and heritage for rovers application, despite consuming an order of magnitude more power with respect to LEON processors [13]. The sizing of the Rover's OBDH components considered the high processing demands of image processing, with significant margins to ensure adequate performance.

Finally, the Landers require much less processing power than all the other vehicles, however they are equipped with an extra computer to manage cruise and EDL phases for both Rovers and Landers.

Regarding the data bus, a conventional MIL-ST-1553B has been chosen for the Orbiter, while Rovers and Landers take advantage of an innovative application of the CAN bus. The main buses are then accompanied by faster point-to-point connections for all the high data rate instruments and sensors, through SpaceWire. For this purpose, SpaceWire routers are implemented in the I/O boards. SpaceWire is also used for OBC boards interconnection (through the backplane), together with power harness.

Finally, the RF transmission lines are implemented as point-to-point differential buses (such as RS422 and LVDS) for their superior rejection of noise and interference.

4.8. Thermal Control System

The TCS of the *MONARCH* mission mainly focuses on maximizing the operational efficiency by maintaining each and every component, of both the Orbiter and the ground vehicles, within their operational temperature limits.

Firstly, the operational temperature limits for the most important components were tabulated and a mono-nodal thermal analysis for both the worst case hot and cold conditions was performed to preliminarily decide the passive and active thermal control systems, as well as size radiators and heaters. Survival, operational and estimated temperatures have been reported in the graphs below [5], [4].

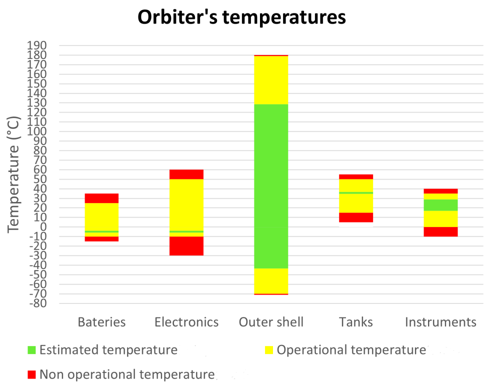

Figure 4: Temperature Limits Orbiter

Upon deriving insights from the mono-nodal analysis, the selection of insulation for the ground vehicles was deliberated: Silica Aerogel (α-0.3, ε-0.015) [23] was chosen over traditional MLI due to its superior adaptability to the atmospheric and environmental conditions on Mars. Additionally, White Paint ZOT (α-0.18, ε-0.85) [14] was identified as the optimal surface finish for the ground vehicles.
Afterwards, a multi-nodal analysis [25] [1] was performed to refine the chosen architecture: this involved defining multiple nodes for both the Lander and Rover, refining radiator sizes to 0.42 m^2 for the Lander and 0.49 m^2 for the Rover, and opting for a two-layer Silica Aerogel insulation totaling 16 mm in thickness.
The eMMRTG active fluid loop has to be further analysed for the Rover in order to assess the capability to reject the waste heat generated.
For the orbiter, in accordance with the mono-nodal analysis, it was determined to employ louvers to reduce power consumption during eclipses, MLI (Multi-Layer Insulation) as external insulation, and RTV 566 ($k = 0.3\ W/mK$) [9] as insulation for the batteries. A multi-nodal approach was then adopted to refine previous considerations and allowed to obtain preliminary values for the radiator area (2.5 m^2), power needed (up to 40 W) and the thickness of the insulating layer for the batteries (0.03 m^2). Further studies should be focused on the development of a more detailed multi-nodal analysis to allow the computations of more localized heaters and power consumptions. Another point of interest should be the development of a multinodal analysis for the cruise stage.

Figure 5: Temperature Limits Lander

4.9. Electrical Power System

The EPS of the *MONARCH* mission deals with the production, storage, distribution and control of electrical power on all vehicles.
Due to the pivotal nature of the subsystem, a baseline system-level margin of 20% on the power has been taken into account for each vehicle [10]: this lead to a sightly oversized system with an additional level of robustness for emergencies compliance and foresight. The two land vehicles and the Orbiter include a PDCU and they all run on a main power bus of +28V; power requests were evaluated with a further subdivision by day/night or sunlight/eclipse, for each mode and for each vehicle and assembly.
The Orbiter adopts two symmetrical Silicon solar arrays, for a total of 13.5 m^2, with two degrees of freedom each, coupled with a secondary Nickel-hydrogen battery pack; this vehicle will also be responsible to provide power to one of the two cruise assemblies during the interplanetary trip, and its size allows it to be perfectly able to provide an adequate power amount even in case the two rotation hinges

malfunction or stop working. The other cruise assembly will be powered by 4 m^2 of a circular solar array placed on top of the Cruise Stage, with a small Li-ion battery pack for specific maneuvers done while hidden from the Sun's direct view.
Each of the Landers will be powered by 14.2 m^2 of deployable GaAs solar cells arrays, along with a Li-ion battery pack of around 17 dm^3, to remain operative during the long Martian winter nights at the latitude of the landing spot, even when the solar array will inevitably be mostly covered by thin martian dust.
Each Rover will mount an eMMRTG, which will provide continuous power through all days and nights of the mission, allowing the moving vehicles to most likely out-live the Landers. The reactors will work alongside a Li-ion fully redundant small battery pack for the most power-intensive modes; eMMRTGs are still an on-going project for NASA[18], but the launch date for *MONARCH* is far away enough in time to realistically propose the use of this new improvement on the classical MMRTG.
The two Entry Capsules will be identical in design and will each mount a small thermal Li/FeS_2 primary battery pack, to deal with the entry and landing operations.

4.10. Configuration

The Entry Capsules are stacked respectively on top of the Orbiter and on the Cruise Stage as reported in fig. 6. Separation is performed through the release of a pyrotechnic clamp-band system, along with a set of preloaded push-away springs. The detachment of the heat shield and of the landing segment, i.e. Lander and Rover, from the back shell is obtained through separation nuts.
On the Orbiter, the instruments are clustered on one face, that is nadir pointing and thermo-mechanically decoupled from the spacecraft, while the 2.2 m high gain antenna is placed on the opposite face with a gimbal to extend the communications window. The size of the vehicle is dictated by the large dimensions of the tanks, placed to obtain a bulky configuration to counteract the risk of buckling. Particular attention is placed on the FoV of star trackers and on the instrument cameras.

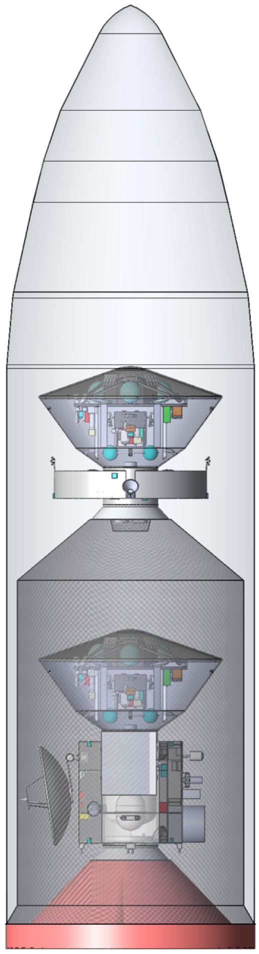

Figure 6: Space segment configuration at launch

The Lander configuration is mainly influenced by the need to sustain and deploy the Rover, thus a wide upper deck with two redundant sets of deployable ramps is adopted. The presence of eMMRTG on the Rover constrains the position of the instruments on the front of the vehicle to balance the CoG and to reduce the impact of radiations.

4.11. Robotics & Mechanisms

MONARCH mission certainly requires a specific design of some robotic components in order to achieve its objectives, both on the land vehicles and on the Orbiter. First of all, a 3-

DoF robotic arm with a grapple installed at the end-effector has been designed, for the two Landers only, to lift and deploy on the Martian soil the 'Seismometer' and the 'Heat flow and Physical Properties Package'. Then, a 2.1 m telescopic boom is mounted on both the Rovers and the Landers, at the top of which is installed a 'Meteorological Instrument Package' containing sensors to study Mars' atmosphere. This telescopic boom will be extended and retracted using a 'Bi-storable tubular extendable member' technology and is necessary to avoid having any kind of interference caused by the presence of the vehicle. Afterwards, for what concerns the Rover's locomotion system performances, the Bekker trafficability model has been used to determine the most suited wheels' speed and dimensions[8], and a 'Rocker-Bogie' suspension system was chosen due its known advantages in terms of stability and capability to overcome obstacles. Finally, attention must be paid on the 2-DoF gimbal developed for the pointing of the Narrow Angle Camera installed on the Orbiter, necessary in order to avoid having continuous slew maneuvers.

4.12. Structures

The structure of *MONARCH* is responsible for each segment's survivability in all loading conditions encountered during the mission, providing support and protection to all on-board payloads. The primary structure, made of Aluminum Honeycomb sandwich panel with a tensile strength in the order of 100 MPa, is able to withstand dynamic and static load in the most severe phases, like EDL and Launch. The design of both assemblies is compliant with the selected launcher requirements in terms of total mass, CoG height, lateral and longitudinal natural frequencies, allowable volume and flight envelope. A central cylinder with the same diameter of the selected adapter interface (PLA6 1194) is present in both Orbiter and Cruise Stage in order to sustain the Entry Capsule from a buckling point of view. The choice of the material reflects the need for low density and high mechanical properties, in addition to the thermal behaviour required by the TCS. Both assemblies are presented in Figure 7 and 8.

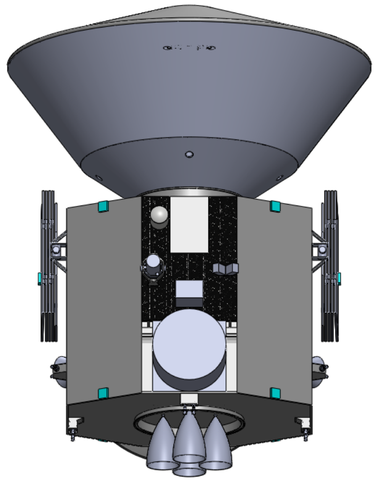

Figure 7: Orbiter assembly configuration at launch

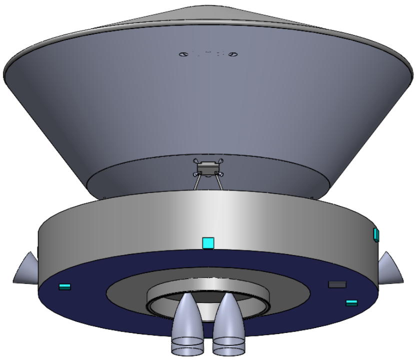

Figure 8: Cruise Stage assembly configuration at launch

4.13. AIVT, Risk & Cost

To account for technical, programmatic, and uncertainty-related criticalities, a risk analysis has been carried out. The potential impact on the project timeline must next be assessed by evaluating the risk. The severity table proposed by ESA presents significantly small margin, declaring a Catastrophic index for a loss of 30% of data [11]; however, in the context of the preliminary design for the *MONARCH* mission, more conservative margins will be employed, deeming a loss of 70%-75% of science data as catastrophic. A risk mitigation has been proposed benefiting from the knowledge gained from past missions, to identify possible actions. Increasing the number of tests conducted is one possibility to mitigate the impact on the project, but doing so comes at the expense of higher project costs and longer project duration. To evaluate the cost of the *MONARCH* the NASA software Project Cost Estimating Capability has been used. The total cost resulted as 1173.43 million, divided as shown in figure 9.

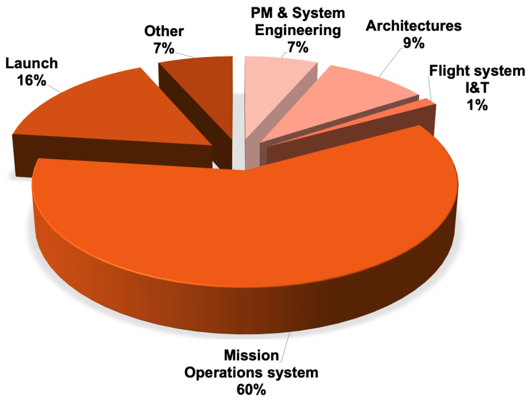

Figure 9: Cost allocation

5. Conclusions

In conclusion, from a Systems Engineering perspective, the feasibility of the *MONARCH* mission is confirmed with multiple advantages. One example is the versatile architecture that provides a successful mission even with a different landing site selection. Moreover, the intrinsic redundancy of the architecture ensures a partial mission success even in case of the loss of one of the two Entry Capsules.

However, key considerations must be addressed for the mission to succeed:

- A sufficient supply of plutonium must be secured, as it is a scarce resource which is produced by few countries, like USA and Russia. The launch year (2041) provides enough time to address and resolve this issue, however, international cooperation might be crucial to solve this aspect.
- Never before have so many vehicles been interconnected for an interplanetary cruise. Each lander is equipped with a dedicated EDL (Entry, Descent, and Landing) and Cruise computer to manage this complex system, which relies on a substantial number of umbilical connectors. Therefore, it is crucial to ensure the reliability of these connectors to prevent them from becoming a single point of failure.
- The mission included a single-launch constraint to ensure feasibility. This, along with the preference for an already existing Dual-Launch-Structure on the launcher, lead to the selection of Ariane 64 as the main launcher, with Falcon-Heavy as a backup vehicle.
- The mandatory US-friendly assembly location due to ITAR regulations must be addressed.

Further enhancements could also be foreseen in the future to maximize the scientific return:

- Martian dust occultation of the solar panels lead to a deep analysis on the possible mitigations strategies and design changes. The final design has a wide enough area of solar cells to survive until the end of the mission, but possible cleaning strategies could revolve around vibrations, tilting the panels to exploit martian winds, use of the robotic arm; of course all of this leads to a more complex design.
- Specific navigation assets [8] could be introduced to enhance the network's capabilities: the Orbiter could be equipped to monitor the positions of the rovers, providing feedback from orbit, while the landers could communicate their relative positions to assist with Vision-Based Navigation.
- Processing power is currently the most limiting factor for rover observations. Martian rovers with autonomous guidance and obstacle avoidance currently spend over 50% of their traverse time on data processing rather than moving. Introducing new space-grade hardware accelerators could significantly improve the efficiency and effectiveness of rover observations.

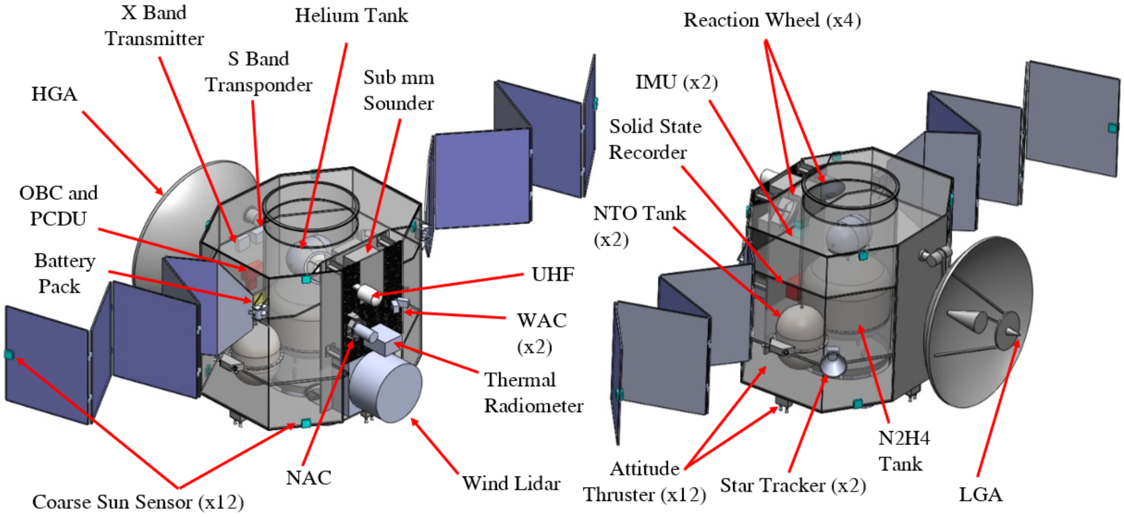

Figure 10: Orbiter configuration

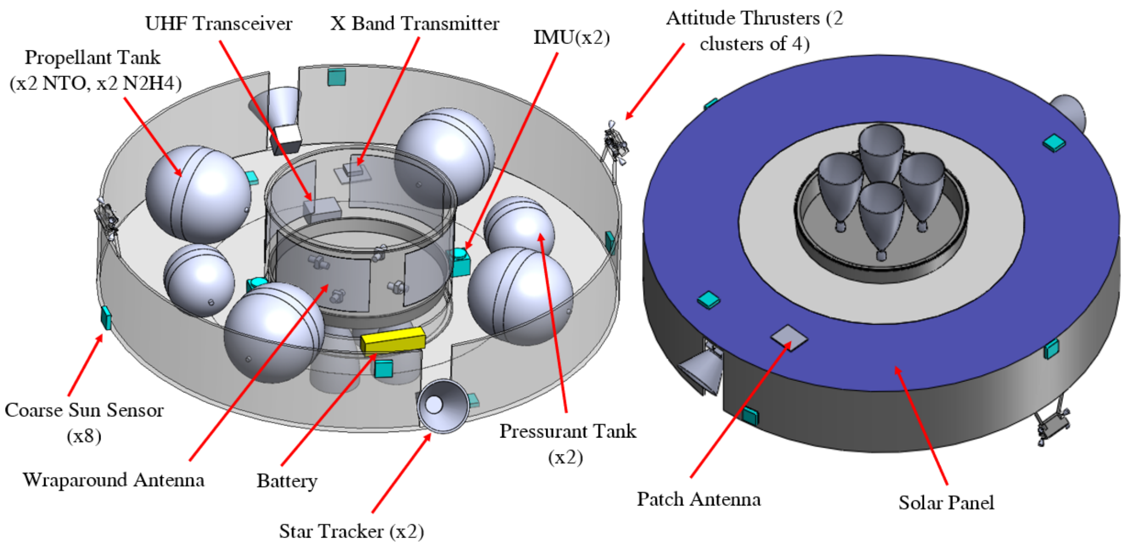

Figure 11: Cruise Stage configuration

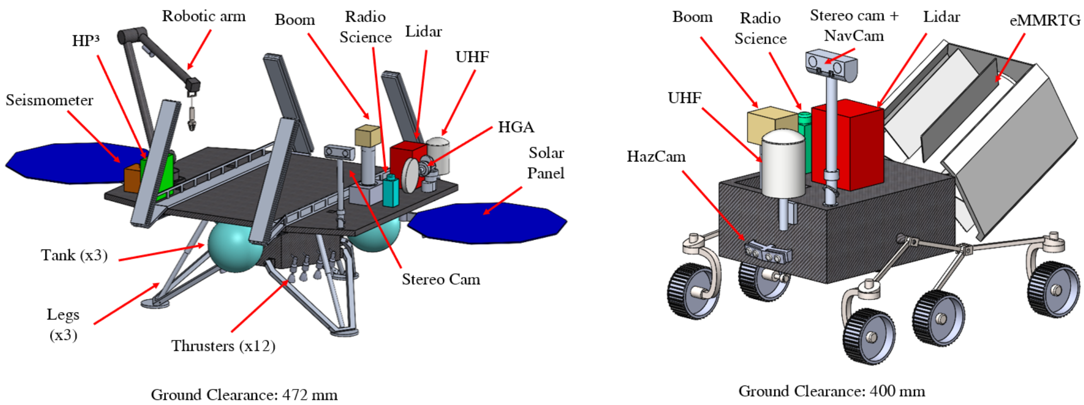

Figure 12: Landing segment configuration

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