Mars Magnetospheric Multipoint Measurement Mission (M^5)

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Abstract

Mars Magnetospheric Multipoint Measurement Mission (M^5) is a multi-spacecraft mission proposed to study the dynamics and energy transport of the Martian magnetosphere. Particular focus lies on the largely unexplored magnetotail region, where signatures of magnetic reconnection of the Interplanetary Magnetic Field (IMF) has been found. Further, to study the dynamics of the Martian magnetosphere depending on the solar wind conditions, previous knowledge of the solar wind condition is needed. Finally, to resolve the three-dimensional structure of the Mars magnetosphere, multipoint measurements are required. Taking these considerations into account, M^5 is a five spacecraft mission, with one solar wind monitor orbiting the Mars in a circular orbit, and four smaller spacecraft in a tetrahedral configuration orbiting Mars in an elliptical orbit, spanning the far magnetotail up to 6 Mars radii.

1 Introduction

1.1 Scientific Background

A plasma is a collection of charged particles exhibiting collective behavior. It makes up about 99% of the observable matter in the universe, and examples range from lightning strikes to clusters of galaxies. The solar wind is composed of plasma, as is the ionosphere of planets. The interaction between these two plasmas, and if present, with the magnetic field of the planet, is studied by both *remote sensing* and *in-situ* measurements. Terrestrial planets like Earth have an intrinsic magnetic field driven by an active internal dynamo. As a result of the progressive cooling of the planet, this dynamo can fade away. An example of these post-dynamo planets is our close neighbor: Mars.

Mars possesses strong magnetic anomalies (crustal fields) of up to 300 nT [1] at its surface, and lacks a global intrinsic magnetic field [2]. However, the interaction of its ionosphere with the solar wind results in an induced magnetosphere at Mars (see Fig. 1). The Interplanetary Magnetic Field (IMF) drapes around the planet, forming a magnetotail with two lobes that are separated by a plasma sheet, directed in opposite directions [3]. This induced magnetotail is variable depending on the solar wind conditions. An example of this variability is the modifications in the IMF which induce a reorientation (and flapping) of the tail [4]. Despite comprehensive studies of the Martian environment of previous missions (see 1.2), the tail region has never been characterized in detail by *in-situ* measurements.

Magnetic reconnection is a fundamental plasma process where magnetic energy is converted to kinetic energy. It has been studied at Earth with formation missions like Cluster or Magnetospheric MultiScale (MMS). Similar processes occur on other magnetized and unmagnetized planets. On Mars, both measurements [6], [7] and simulations [8] suggest that reconnection occurs between the IMF and the crustal magnetic fields. There are also signatures of reconnection of the IMF in the tail region that potentially influence ion flow velocities and would play a role in the dynamics of the magnetotail. Reconnection is not the only physical process of interest that takes place in the magnetotail. The magnetotail is one of the main paths for planetary ions to escape from the Martian atmosphere, in a process referred to as *atmospheric escape* [9]. Therefore, a mapping of the properties of the Martian magnetotail complements ongoing studies of this important process. This is vital for the understanding of how the habitability of Mars has changed over time.

Moving from the Martian night side, the magnetotail, to the day side, crucial features of the induced magnetosphere are the *bow shock* and the *magnetic pileup boundary*. An overview of the Martian magnetosphere can be seen in Fig. 1. Both of these regions have been studied by previous space missions, notably the Mars Atmosphere and Volatile EvolutioN (MAVEN), but no systematic characterization of their variability depending on solar wind conditions have been performed [10]. Plasma waves, including Langmuir waves and ion-acoustic waves, have been observed at the Martian boundaries [11], and are connected to both energy transport at said boundaries and to plasma instabilities.

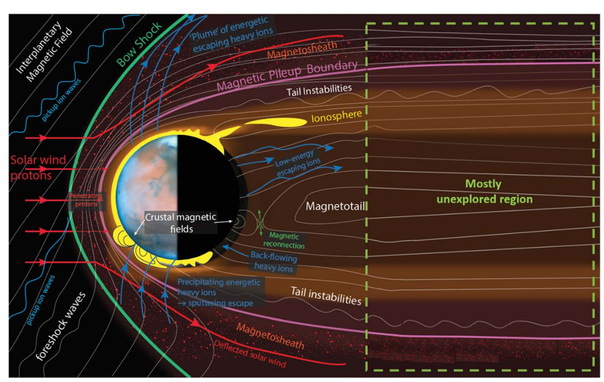


Figure 1: Overview of the Martian induced magnetosphere taken from [5]: The IMF is drapes around the planet, forming a highly dynamical magnetotail, that is still open to be studied comprehensively.

In order to characterize boundaries, current systems and to study processes like reconnection, a multi-spacecraft formation is needed to properly differentiate spatial from temporal variations. Moreover, there is currently no solar wind monitor at Mars, which is needed to investigate the variability of the magnetosphere depending on solar wind conditions.

1.2 Previous & Upcoming Missions

In the last decades, multiple missions have targeted the red planet. This includes: Mars Odyssey [12], Mars Express [13], Mars Reconnaissance Orbiter, and the MAVEN [14] orbiter. The main science topics of these and other missions were the search for water, looking for bio-signatures, and exploring the surface of Mars for future robotic and human exploration. To date, MAVEN has been the only mission fully capable to explore the properties of the magnetospheric plasma around Mars, studying atmospheric escape and the plasma in the upper atmosphere. The upcoming mission *The Escape and Plasma Acceleration and Dynamics Explorers* (EscaPADE), which is scheduled to launch in 2025, will study the flow of energy in and out of the atmosphere, as well as the flow of ions in and out the Martian atmosphere [15].
Mars continues to capture the interest of the wider space physics community, as shown by the *Voyage 2050 Senior Committee Report* [16]. This report was written by a committee of senior scientists to identify key science areas for the ESA's science program during the period 2035-2050. Two of these themes are "Magnetospheric Systems" (3.1.1) and "Plasma Cross-scale Coupling" (3.1.2). According to the senior committee, *"important questions such as "How is energy and matter transported in induced magnetospheres" still need to be answered by studying entire magnetospheres as complex systems"*.
One could argue that the Mars environment has been investigated in detail. However, as seen there has been only one specialised plasma physics mission. Furthermore, how the magnetosphere changes with solar wind conditions, how energy is transferred across different scales - both spatial and temporal - and also the Martian magnetotail remains mainly unexplored until now. The main objectives of the M^5 mission come from this heritage and this current interest of the scientific community, and are stated in the following section.

1.3 Scientific Objectives

The scientific theme of the M^5 mission is to:

"Understand how the variable solar wind conditions influence the dynamics and energy transport of the Martian induced magnetosphere".

This theme is divided into two science questions, which can be found in Table 1. The first question (**Q1**) focuses on the dependency of the Martian magnetosphere on solar wind conditions. This dependency is evident in phenomena like tail flapping, meaning a shear movement of current sheets [4], or the strong variation of the spatial position of the bow shock and magnetic pileup boundaries [17]. The global current system of the Martian magnetosphere is also subject to the variations of the solar wind, and has only been estimated on a year-mean scale from MAVEN data [18]. These variations have been observed by MAVEN, but information about the spatial and temporal evolution depending on the solar wind conditions, as well as observations of the more distant part of the tail are lacking.
The second question (**Q2**) relates to energy transport in the Martian magnetosphere. Phenomena important for energy transport at Mars have been observed and seen in numerical simulations, including reconnection [19, 20], and low frequency waves in the magnetosheath and the upstream solar wind [21, 22]. The analysis of the global and ion-scale energy transport is based on *in situ* observations. In order to provide a complete three-dimensional picture of this transport, M^5 will be composed of a tetrahedral constellation of four spacecraft capable of probing the magnetospheric boundaries in 3D.
In addition to these two primary scientific questions ($Q1$, $Q2$), M^5 will be able to tackle two other secondary scientific questions.
The third question (**Q3**) concentrates to the propagation of the solar wind in the solar system. Continuous space weather observations are getting increasingly important, especially in preparation to future human exploration of our planetary neighbor, Mars. Due to the high variability of the Martian magnetosphere, events like solar storms are potential threats due to enhancing the particle precipitation into the atmosphere that can cause disruption of technologies. A continuous observatory of the solar wind at Mars not only extends the "orchestra" of solar wind monitors, but also provides information on the evolution of solar transient structures like solar storms and the subsequent reaction of an object without intrinsic dipole field on different solar wind energy inputs.
The fourth question (**Q4**) is related to the possibility that reconnection in the Martian magnetotail is not the only process driving the energy transport. At the present moment, only indications of magnetic reconnection have been found at Mars. Therefore, it is not clear, if excluding magnetic reconnection, there are other processes driving the energy transport at the Martian magnetotail.

1.4 Mission Profile

The M^5 mission consists in total of five spacecraft. Four identical *Magnetospheric Formation Orbiters* (hereafter MFOs), which will be placed in an elliptic orbit in a tetrahedral formation (Sec. 4.3). Their goal is to investigate the Martian magnetotail and the boundary regions, addressing all science objectives. The fifth spacecraft is the *Solar Wind Observatory* (hereafter SWO). Its target or-

Table 1: Scientific questions and objectives of the M^5 mission.

Primary scientific question	**Primary scientific objectives**
Q1: How do the Martian magnetospheric system's structure and dynamics depend on solar wind conditions?	O1.1: What are the dynamics and orientation of boundary regions, with particular interest for their dependence upon solar wind conditions? O1.2: What is the structure of the Martian magnetotail on different scales, with particular interest for its dependence upon solar wind conditions? O1.3: What is the dynamical structure of the current system in the Martian magnetosphere, with particular interest for its dependence upon solar wind conditions?
Q2: How is energy transported within the Martian magnetospheric system on ion scales and above?	O2.1: Is magnetic reconnection observed in the magnetosphere tail, and if so, where and how? O2.2: What are the direction and temporal evolution of low frequency plasma waves?
Secondary scientific question	**Secondary scientific objectives**
Q3: How does the solar wind propagate through the solar system?	O3.1: What are the temporal variations of the upstream solar wind conditions at Mars?
Q4: Excluding magnetic reconnection, are there other processes driving the energy transport at the Martian magnetotail?	O4.1: Are other energy transport processes observed at the Martian magnetotail that exhibit signatures different to magnetic reconnection?

bit is a circular orbit around Mars and it will characterize the solar wind properties around Mars during the whole Martian year. As a result of the chosen orbit it will spend a part of its orbit in the magnetotail, covering a region similar to the one explored by MAVEN. Furthermore, it acts as a data relay for the MFOs to Earth. The MFOs and the SWO alone and in transit configuration can be seen in Fig.2.

As mentioned above, a tetrahedral formation of four spacecraft is required in order to resolve both the spatial and time scales, allowing a three-dimensional mapping of the boundary regions, even when the boundary and orientation is unknown. This constellation also allows mapping of magnetosphere currents, using the curlometer technique [23] to derive currents from magnetic field measurements. Furthermore it will be used for measurements of wave directions and time dependency using the wave telescope technique [24].

2 Traceability of requirements

The measurement, instrument, orbit, and functional requirements are derived from the science questions and objectives stated in Table 1 by using a traceability matrix. By looking at the measurement region, physical entity, timing demands, and specific measurement needs (e.g. range and accuracy), these requirements are derived and matching heritage instruments have been selected. Table 2 shows the required instruments on each spacecraft, both on SWO and the MFOs. Condensed instrument requirements (e.g. timing and specific region depending on the exact objective) for each instrument from different measurement requirements are stated below, with the specific payload selected given in Section 3.

Magnetometer: in the Martian magnetosphere, absolute range: 3000 nT, absolute accuracy: 0.5 nT, temporal resolution: 128 samples/s;
in the solar wind, absolute range: 500 nT, absolute accuracy: 0.5 nT, temporal resolution: 128 samples/s.

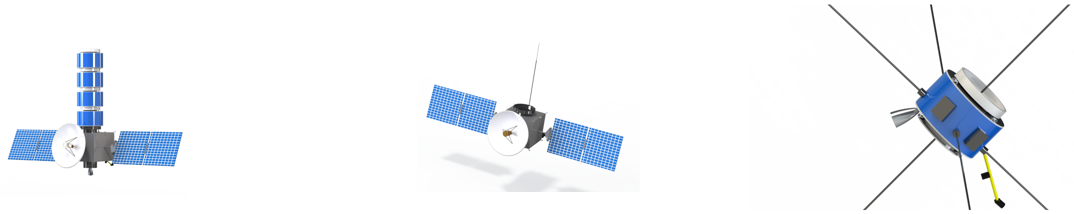
Ion moments: in the Martian magnetosphere, energy range: 1 eV to 30 keV, energy resolution (ΔE/E): 25%, temporal resolution: 5s, FOV: 360° x 90°, detect H+, O+, O2+, CO2+;
in the solar wind, energy range: 10 eV/q to 25 keV/q, energy resolution (DeltaE/E): 25%, temporal resolution: 5s, FOV: 180° x 40°, detect H+, He++, higher mass.

Electron moments: in the Martian magnetosphere, energy range: 50 eV to 10 keV, energy resolution (ΔE/E): 25%, temporal resolution: 5s, FOV: 360° x 120°;
in the solar wind, energy range: 10 eV to 5 keV, energy resolution (ΔE/E): 30%, temporal resolution: 5s, FOV: 180° x 40°.

Electric field: in the Martian magnetosphere, absolute range (E): ±300 mV/m, accuracy: 1 mV/m or 10%, temporal resolution: 1 to 200 Hz. The specific set of instruments present on the M^5 mission, and its ability to meet the criteria stated, is presented in the following section.

3 Payload

An overview of the payload and its requirements are presented in the following section.



(a) Solar Wind Observatory and Magnetospheric Formation Orbiters in stacked configuration

(b) Solar Wind Observatory

(c) Magnetospheric Formation Orbiters

Figure 2: Three-dimensional rendering of the spacecraft forming the M^5 mission.

Table 2: Scientific objective addressed by each instrument used by the M^5 mission. The big dot ◯ stands for SWO and the small dots • for MFOs.

Science question	Science objective	Magnetometer	Ion spectrometer	Electron s pectrometer	Langmuir probe	Dipolar antennas
Q1	O1.1	◯ ••••	◯•			
	O1.2	◯ ••••	◯•	◯	••••	
	O1.3	◯ ••••	◯	◯		
Q2	O2.1	••	••			
	O2.2	••••			••••	••••
Q3	O3.1	◯	◯	◯		
Q4	O4.1	••	••	••		••

3.1 Flux Gate Magnetometer (FGM)

The magnetometer that will be purposed for the mission is a 3-axis fluxgate magnetometer with heritage taken from Thermal Emission Imaging System (THEMIS). It will be mounted on a 2 m deployable boom. Possible providers for the instrument are provided by Germany (Technische Universität Braunschweig), and Austria (ASA, Institut für Weltraumforschung). FGM measures the magnetic field in 3D and consists of two ring-core elements made of an ultra-stable 6-81-Mo permalloy band of dimensions 2 mm x 20 μm fixed with a bobbin and each of different radius orthogonal to each other. Presented in Table 3 is the engineering requirements for the FGM.

Table 3: FGM engineering requirements

Range	3000 nT
Offset stability	0.5 nT / 12 h
Absolute vector accuracy	0.05%
Resolution	20 pT
Sample rate	128 vectors/s
Attitude knowledge	<0.05°

3.2 Ion Spectrometers

An electrostatic analyser is used to measure the ion energy distribution function. In the case of the single instrument placed on the SWO, it will be used as an ion energy spectrometer. Its heritage is the Solar Orbiter's SWA-HIS instrument, which is shown in Table 4 [25].
In addition, the instrument on the MFOs will use magnets to act as a mass over charge spectrometer. As heritage the Ion composition analyser (ICA) instrument on Rosetta is considered [26]. These requirements are presented in Table 5. The ion mass spectrometer will measure the 3D distribution function of the positive ions to study how the particles interact with the solar wind.

Table 4: SWA-HIS engineering requirements

Particle species	H+, O+, O2+
Energy range	10 eV/q to 25 keV/q
Energy resolution (ΔE/E)	25%
Temporal resolution	5 s
FoV	180° x 40°

Table 5: ICA engineering requirements

Energy range	1 eV to 30 keV
Energy resolution (ΔE/E)	25%
Temporal resolution	5 s
Angle coverage	360° x 90°
Carbon foil TOF analyzer	Proton flight of time 12 to 7 ns
Anode detection resolution	22.5°

3.3 Electrostatic electron analyser

Besides the ion energies, the electron composition is also of interest. To do so, an electrostatic electron analyser will be employed on all five spacecraft. Their heritage is from the Solar Orbiter (SWA-EAS) instrument [25]. The SWA-EAS requirements are presented in Table 6 The solar wind electron analyser will measure the effects from the electron impact ionization from the solar wind as it enters the Martian atmosphere.

Table 6: SWA-EAS engineering requirements

Energy range	50 eV to 10 keV
Energy resolution (ΔE/E)	25%-30%
Temporal resolution	5 s
FOV	360° x 120° / 180° x 40°

3.4 Electric field instrument

There will be one electric field instrument using 6 booms (4 wire booms, 2 telescopic booms) on each MFO in order to measure the 3D electric field vector. Two orthogonal probes will in addition have Langmuir probe capabilities. This will be used to measure the temperature and density of the plasma. The combined instrument has heritage from the electric-field and wave instrument (EFW) onboard the ESA Cluster mission [27], which can be seen in Table 7.

Table 7: Electric field antenna engineering requirements

Absolute range (E)	+-300 mV/m
Accuracy	1 mV/m or 10%
Temporal resolution	1 to 200 Hz

4 Mission Design

To fulfill the M^5 mission requirements, five spacecraft are required. Four MFOs are essential to probe the Martian magnetotail and magnetospheric boundary regions in a three-dimensional formation. Also, the SWO, which orbits the planet in a circular orbit of 5 Martian radii, provides data from the solar wind conditions and offers complementary information for the magnetospheric measurements. The SWO is responsible for controlling the formation of the MFOs, and acts as a data down link relay to Earth for the MFOs. A detailed sketch with demensions of the SWO with stacked MFOs can be seen in Fig. 6.

4.1 Ground Segment

The ESA Deep Space Antennas network, which include the antennas located in Cebreros (Spain), Malargüe (Argentina) and New Norcia (Australia) will be used as ground segments for the mission. Science operations will take place at ESAC, close to Madrid.

Table 8: ΔV budget

Maneuver	Δ_V [m/s]	Propellant Mass [Kg]
DCM	(3.2) 30	6.4
OI	2668	3552
CM	75	21
LPM	1596	50
FC	1600	43

4.2 Launch and Propellant

The M^5 mission is designed to be launched on an Ariane 64 launcher from Kourou, French Guiana. After the launch, the thrusters of the five spacecraft will get them to orbit with MMH/N204 or Hydrazine monopropellant.

4.3 Orbit and Maneuvers

After launch, the five spacecraft will fly in a heliocentric elliptic transfer orbit to Mars. Initially the four MFOs are stacked on top of the SWO. With this configuration the spacecraft, see Fig. 3, will perform a Deep Space Correction Maneuver (DCM) before reaching Mars' sphere of influence and is then performed to enter a slightly elliptical Insertion Orbit (IO) ($5R_m \times 6$ R_m) with a 30° inclination around Mars. Next, the four MFOs detach from the SWO and from each other. The SWO performs a Circularization Maneuver (CM) at the periapsis of the insertion orbit entering its nominal orbit ($5R_m \times 5R_m$, RAAN=158°). The MFOs reach the apoapsis of the insertion orbit and perform a Lowering Periapsis maneuver (LPM). Their target orbit has a periapsis equal to $1.8R_m$ and they will orbit in a cartwheel helix Formation Configuration (FC). The choice of the MFOs orbit ($6R_m \times 1.8$ R_m, RAAN=158°) satisfies the scientific requirement of orbiting in the magnetotail. In particular, thanks to the J_2 effect, the time spent in the tail is increased by a factor of 5 to 280 days. A schematic of the orbits can be seen in Fig. 3.
The ΔV required to perform these maneuvers and the propellant mass burned during the firing is presented in Table 8.

4.3.1 State Modes

The SWO and MFO will operate in seven modes as shown in Fig. 4. Each of these modes will be used in different mission phases, therefore consuming different amounts of power for which specifications will need to be met. The stae modes are presented in Figure 4

- **Safe Mode**: Traveling to Mars and save power.
- **Commissioning Mode**: Turning on instruments and payloads to perform testing and health check.

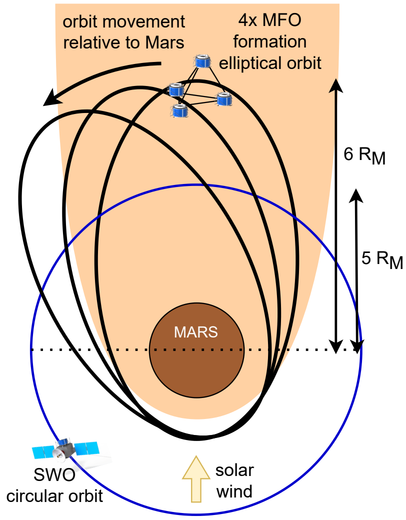


Figure 3: Final orbit configuration of SWO and MFO; the orbit of the MFOs will apparently move relative to Martian reference frame, moreover the orbit precesses due to the oblateness of the planet (J_2) as described in Section 4.3

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- **Orbital Control Mode**: Maneuvering with thrusters.
- **Science Mode**: Instruments on and measuring.
- **Burst Mode**: Science Mode with increased data rate (only MFO).
- **Sun Safe Mode**: Entered automatically when battery voltage drops below the settled voltage threshold.
- **Downlink Mode**: To transmit data.

5 Space Segment

The SWO and MFO carry different payloads, but mostly share the same bus with only slight differences. Hence, the subsystems discussed below in Fig. 5 will cover both spacecraft, unless stated otherwise.

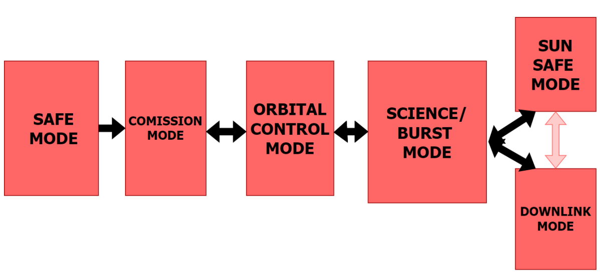

Figure 4: State Mode Diagram

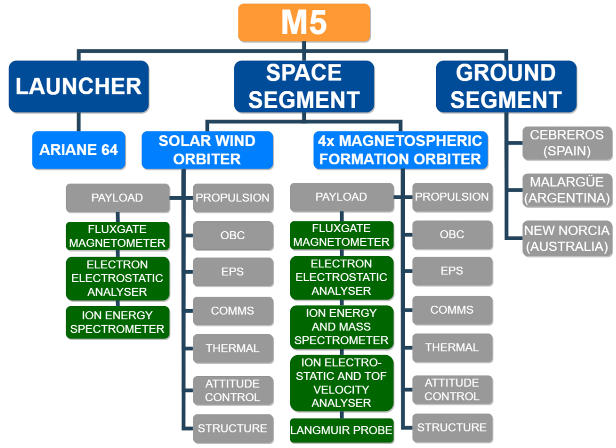

Figure 5: System overview.

5.1 Structure and Spacecraft Design

The primary structure of both spacecraft consists of a 0.8m cylindrical core that encloses the propellant tanks. The material used is an aluminium honeycomb sandwich structure with graphite composite face sheets, providing enough stiffness to sustain the launch loads and induced vibrations. As mentioned, the MFO are stacked on top of each other using a locking mechanism which will be designed in further stages. A section cut of the general structure is presented in Fig. 6.

5.2 Telemetry & Telecommand

Additionally to performing scientific tasks, the SWO serves as a communication hub between the MFO formation and the Earth ground station. Therefore it contains a high gain dish antenna (HGA) with a diameter of 2.5m to communicate between the SWO and ESA's Deep Space Antenna (DSA) network. Additionally, each of the five spacecraft carry an identical low gain dipole antenna (LGA) to communicate between the SWO and the MFOs.

5.2.1 Data and Link Budget

The datalink between Earth and Mars is obtained by the SWO in the X-band. The pointing requirement ($< 0.3°$) is achieved by pointing the HGA dish semi-independently from the spacecraft body. The MFOs communicate with the SWO in the S-band. The link budget is presented in Table 9. Table 10 shows the maximum rate at which the spacecraft produce data.

Table 9: Link budget

Direction	Min rate	Max rate
Mars to Earth	0.45 Mbps	24 Mbps
Earth to Mars	4 kbps	256 kbps
MFO to SWO	38 kbps	475 kbps
SWO to MWO	38 kbps	475 kbps

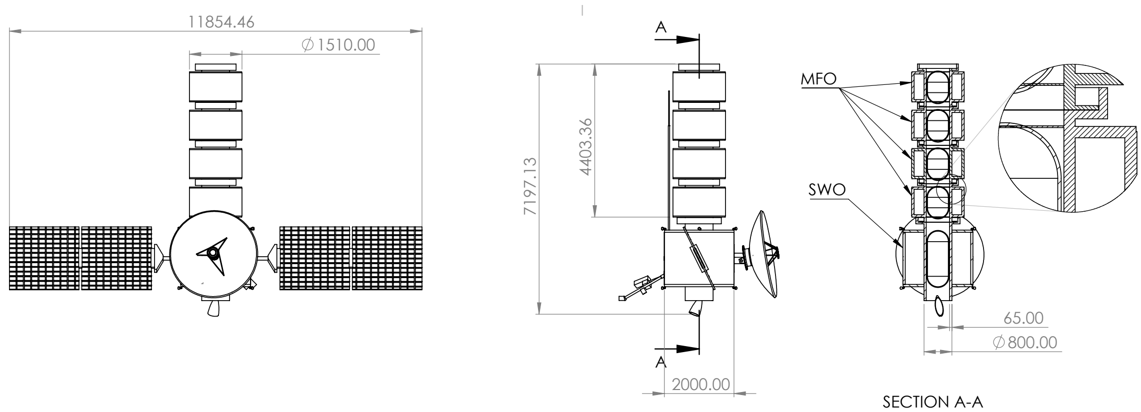

Figure 6: Spacecraft structure details in the stacked configuration and general dimensions in millimeters.

Table 10: Maximum combined instrument data rate

Unit	Data rate (kbps)	Total Time Acquisition
SWO	7.3	50 %
MFO	24	65 %
Max. tot.	105	-

To handle the amount of data received from the MFO constellation to the SWO and back to the ground station it is necessary to minimize the downlink time. During a timeframe of 24 h the data collected on average will for the SWO in worst case be of a maximum of 7 h, when the spacecraft is furthest from Earth ($4{*}10^8$ km), and the best case 35 min ($5.5 * 10^7$ km). For the MFO constellation, the corresponding numbers will vary from 3 h (20337 km) to 10 min (5762 km).

5.3 Power Budget

The batteries used for the SWO and each MFO are 3000 Wh and 1500 Wh Silver-Cadmium batteries respectively. The total power consumption range in normal operations of the SWO will go from 240 W (Science Mode) to 440 W (Downlink Mode). Additionally, the power generated by the solar panels in the sun will be 400 W. On the other hand, the total power consumption range of the MFO will vary between 150 W to 250 W and the power generated in the Sun will be 250 W. The solar array power generation capacity is enough to charge the batteries of the spacecraft between eclipses.

5.4 Thermal budget

The thermal modelling of the spacecraft shows that to stay inside the nominal operating temperature range ($-20°$C to $60°$C), the SWO and each MFO require a constant heat dissipation of 240 W and 150 W respectively. As payload heat dissipation alone does not reach the required level, heaters are used to generate the required total heat. No cooling is required to maintain the spacecraft temperature. The thermal budget for the science mode of the SWO and the MFO are presented in Fig. 7 and Fig. 8.

5.5 Mass budget

To calculate our mass budget we identified relevant subsystems for which we derived the equivalent mass, adding a margin from 5% to 20%. From there we derived the dry mass with and without the overall margin of 20%, which is presented in Table 11.

Table 11: Final mass budget

Mass budget	SWO [kg]	1 MFO [kg]	Margin
Dry mass	465	164	-
Dry mass (marg)	558	197	1.20
Propellant	3711	103	1.10
Total mass	4549	300	-
5749 kg	-	-	-

5.6 On-Board Computer

Most of the selected scientific instruments enforce lossless compression on their measurement data or stream low resolution data and store the high resolution to be transmitted only on demand, the data volume produced by the instruments (derived from datarates presented in Table 10) already fits inside our link budget table 9. Therefore, it is no need for a high performance computer or excessive data handling.

5.7 Attitude and Orbit Control

For attitude determination, each spacecraft will use two star trackers. The SWO carries four reaction wheels for standard attitude and pointing control and a total of 12 thrusters. Each of the spin stabilized MFOs will also carry 12 thrusters in total.
The solar wind observing instruments of the SWO require a solar wind pointing during science mode operations with an accuracy of $< 10°$. The high gain antenna of the SWO requires a pointing to Earth with less than $0.3°$ error for

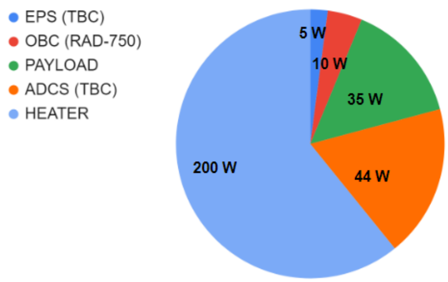

Figure 7: Thermal budget SWO Science Mode

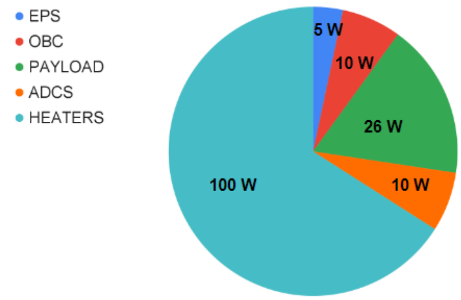

Figure 8: Thermal budget MFO Science Mode

downlink mode. The HGA can be pointed independently from the rest of the SWO spacecraft body. The low gain dipole antennas of the spaceraft are required to maintain an alignment with the normal of the orbital plane with less than 30° of error in order to obtain a data link between the SWO and the MFOs.

5.8 Magnetic Cleanliness

Strict magnetic cleanliness will be required to comply with the magnetic field accuracy and resolution requirements. All soft magnetic materials should be avoided on the spacecraft, in particular close to the magnetometers. All current loops should be minimized and compensated for where possible. Additionally, magnetic dipole moments of the spacecraft should be mitigated or compensated for. All fluxgate magnetometers are placed on 5 m long booms. Each spacecraft has two magnetometers on the same boom to allow for noise mitigation in post-processing.

6 Programmatics

Following, this section describes the organisational aspect of the mission.

6.1 Mission Timeline

The mission will have a total mission timeline of 13 year, with a science mission duration of two years. See Figure 9 for further details.

6.2 Cost Estimate

The mission cost is estimated to 1500 M€ where 47% of the total cost at completion is provided by ESA Space Segment, 10% constitutes of the A64 launcher, 15% for the mission and science operations, 11.5% ESA project and an added margin of 16.5%.

6.2.1 Descoping Options

Given the significant cost of the mission (see Section 6.2), descoping options are possible at the cost of reducing the scientific objectives.

From the MFOs, one or more spacecraft could be descoped to lower mass and cost. However, this would significantly hurt the fulfillment of the science objectives, as a 4 spacecraft formation is needed to answer most science objectives, namely O1.1, O1.2, O1.3, O2.2. A reduction to 3 spacecraft would reduce the 3D picture to a 2D picture, meaning that boundary orientation and movement could not be separated anymore, curlometer and wave telescope technique would only give good scientific return in a limited number of cases. A further reduction to 2 spacecraft would make the answering of the science questions even more challenging, reducing the data to a 1D picture. Therefore, we do not recommend any descoping on the number of spacecraft.

As given by the traceability of the instrument requirements (Table 2, there are possibilities to descope instruments. In particular, the absence of electric antennas on the MFOs would result in a limited loss of scientific objectives (see Table 2).

6.3 Risk Analysis

Some significant risks have been identified for the mission. One risk would be if either the communication with the SWO (posssibly use Mars Reconnaisance Orbiter as a communications relay, but lose the solar wind monitoring capability) or with one (or more) of the MFO would be lost (loss of some science objectives). Another risk would be a failed launch, as well as an error in the orbit insertion, both of which could result in a total loss of the mission. An error in the alignment of the MFO tetrahedron would also be a possible risk. The solar panels or the electric antennas not deploying would cause major difficulties for the mission. These are risks we are aware of and want to minimize as much as possible.

6.4 Space Debris Mitigation

ESA missions are required to abide by space debris mitigation requirements, as set out in [28]. We will therefore ensure that no part of our launcher ends up in a protected orbit such as GTO.

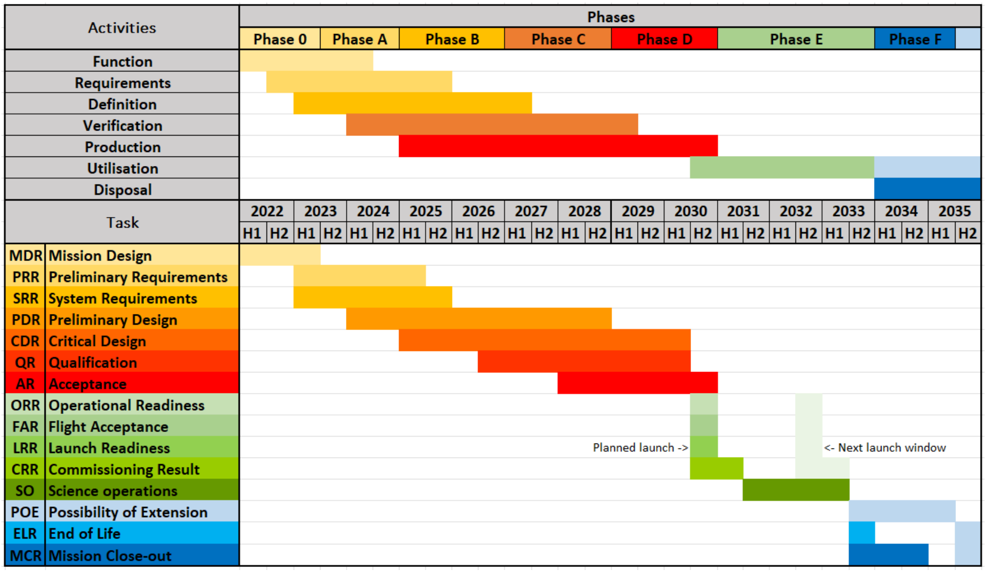

Figure 9: Mission timeline

6.5 Planetary Protection

ESA missions are required to abide by planetary protection standards. M^5 is classed as a Category III mission by ECSS-U-ST-20C – Space sustainability – Planetary protection, as "scientific opinion provides a significant chance that contamination by a spacecraft can compromise future investigations [into the origins of life]" [29]. Therefore, this mission will satisfy the requirements of 5.3.2.1(a-e) of this standard, which require inventorising and retaining samples of organic materials used in our spacecraft, complying with bioburden requirements, and assembling the spacecraft in a cleanroom of ISO class 8 or above.

6.6 Outreach

Outreach is a key aspect for scientific space missions. As a scientific community there is a responsibility to inform taxpayers about how their money is being spent on research. Furthermore, outreach is a key driver for inspiring and encouraging young people to consider careers in STEM. M^5 will be accompanied by a varied and ambitious outreach program, consisting of social media accounts, online and in-person events throughout ESA member states, and open-source educational materials for use in schools. One example would be an arts-and-crafts activity where children can make their own tetrahedron.

7 Mission Envelope

We assumed a baseline of the M7 and L3 calls, the associated technical annexes, and requirements therein (e.g. [30]). The ESA Cost at Completion must be below €550 million for M-class, which is not achievable as shown in the cost analysis. The science objectives for this call were open for M-class, but we note our close alignment to key Voyage 2050 recommendations. We plan to use an Ariane 64 launcher to comply with ESA procurement rules, but which is not normally envisaged for M-Class missions. The spacecraft dry mass of 1608.5 kg including margins of 20% which meets the criteria of the maximum dry weight of 5966 kg for our L-class mission. Our platform and science payload has a TRL ≥ 6, as required. We can incorporate international collaboration, but do not require it. Finally, we envisage a nominal science operation duration of less than three years for our primary scientific objectives. Given the much larger Cost at Completion, increased mass budget and use of the Ariane 64 launcher, we are confident that M^5 can be completed within the constraints of an L-plus mission.

8 Conclusion

This report shows that a multi-spacecraft mission to Mars will be able to extend and complement our understanding of the Martian induced magnetosphere. This understanding will further extend our comprehension of the induced magnetospheric systems itself, and of the interaction of the solar wind with it. Atmospheres are important for the presence of life, and the escape of the Martian one will be better understood by the quantitative characterization of the magnetotail and of the processes taking place there.
In order to study these regions and phenomena on different scales, and in order to separate spatial and temporal variations without having to use imperfect a priori information, a three-dimensional picture of the bow shock, magnetic pileup boundary as well as the magnetotail are achieved thanks to a four spacecraft configuration. The remainder spacecraft will complement the fleet of solar wind observatories in our solar system, crucial in order to provide better data for space weather applications. In

addition to this, Mars is the one of the best candidates for human planetary exploration, and this exploration will only be possible once the danger of radiation to the astronauts will be better estimated. The impact on the public perception of space mission will be significant, considering both the scientific scope of the mission and the fact that it will be the first plasma focused European space mission to the Red Planet.

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