MRO Reverse Engineering Study

Assignment #1

Team 13

P. Code	Surname	Name
10806498	Resta	Filippo
10775619	Ferrari	Francesco
10697841	Giannini	Leonardo
10938069	Frison	Seppe
11060088	Emrem	Mert
10806579	Pirazzini	Edoardo

Space System Engineering and Operations

Prof: M. Lavagna

L. Bianchi, M. Bussolino

M.Sc Space Engineering
A.Y. 2024-2025

Change log	
Issue	*Comments*
1	First release

Contents

1 Introduction

Mars Reconnaissance Orbiter (MRO) is a multipurpose spacecraft launched on August 12, 2005. The mission is still ongoing, providing important information to get a better knowledge of morphology and climate of Mars and helping guide other missions on and around the planet. The following paragraphs present an overview of the mission and its technical aspects.

2 Mission High-Level Goals

The primary objectives of the MRO mission are as follows [7]:

- Acquire information about the present climate of Mars and its seasonal behavior.
- Identifying water-related geographic formations and searching for sites showing evidence of hydrothermal activity.
- Characterize in detail the stratigraphy, geomorphology, and composition of the Mars surface and subsurface at many globally distributed locales to improve understanding of the nature of different types of Martian terrain and their changes over time.
- Identify sites with the highest potential for future Mars missions.
- Transmit and receive scientific data from spacecrafts (S/Cs) involved in Mars missions during after the science goals are achieved.
- Test and provide data to aid in the development of experimental engineering payloads.

3 Mission Drivers

In the MRO mission the following drivers, which have strongly influenced the design of the S/C, can be identified:

- **Data handling** The high-resolution data acquisition performed by the payloads (P/Ls) require a high-performance data processing and transmission system to deliver the data efficiently. The MRO was set out to collect and transmit an unprecedented amount of data for an interplanetary mission. For the Primary Science Phase (PSP) alone, 34 terabits of data was scheduled to downlink, which is more than three times the amount five comparable, previously launched, interplanetary missions together had transmitted [2]. A three meter diameter parabolic antenna was necessary to downlink said data in such amounts. As such, data handling is a key driver of the mission, with significant downstream effects on the rest of the mission's design.
- **Aerobraking** In order to achieve mission success, aerobraking was considered the most suitable option to inject into the Primary Science Orbit (PSO), due in large part to the fuel —and thereby mass—saved (aerobraking reduces the amount of fuel that must be launched from Earth by nearly one-half). Although the Mars Global Surveyor and Mars Odyssey previously utilized aerobraking [6], the maneuver ended up bending a solar panel of the former, therefore making the MRO mission an attempt to improve the braking mechanism on trajectory to Mars. The decision to utilize aerobraking must be made early in the S/C design process, as it significantly changes the desired properties and configuration of the S/C components, particularly those of the solar panels and antenna. Other important aspects, influenced in their totality by aerobraking, are the structural and thermal stresses to which the S/C is subject during this phase. Finally, being a complex and high-risk maneuver, it required continuous attitude and orbital corrections, hence introducing new challenges to the design.

4 Functional Analysis

The MRO mission can be broken down into the functional blocks in Figure 1.

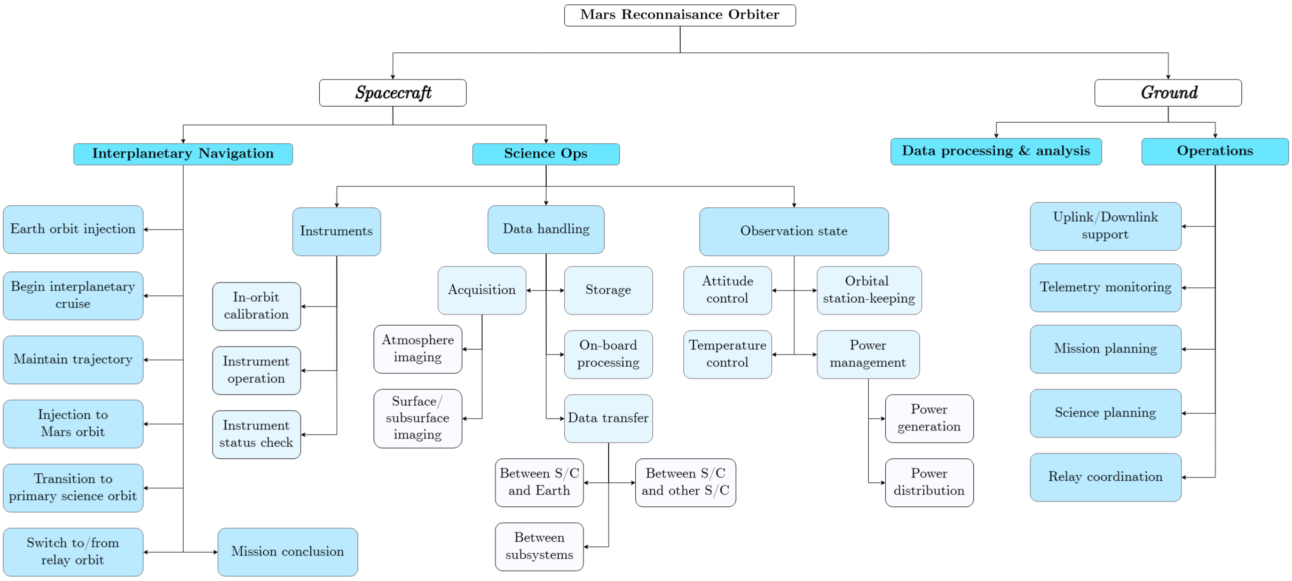

Figure 1: Functional analysis diagram of MRO.

5 Mission Phases

The operational mission of the MRO is divided into several key phases [7]:

1. **Launch and Early Orbit Phase (LEOP)**: MRO was launched aboard an Atlas V-401 rocket. After a brief period of Earth coasting, Centaur upper-stage injected it on an interplanetary transfer trajectory.

2. **Cruise and Approach Phase (CAP)**: After launch MRO began its seven-month journey to Mars. MRO followed a Type-I ballistic trajectory to deliver the orbiter on a southern approach trajectory to Mars. The seven-month cruise phase was partitioned into two distinct mission stages. The first one included spacecraft navigation, and checkouts, while the second one focused on Mars approach.

3. **Mars Orbit Insertion (MOI)**: MRO executed a propulsive maneuver to enter Mars orbit using its main engines while adjusting attitude with smaller thrusters. This phase ended with spacecraft reconfiguration and imaging operations in order to prepare for the next phase.

4. **Aerobraking and Transition Phase (ATP)**: During this phase, the spacecraft dropped into the upper portions of the Martian atmosphere and used the aerodynamic drag to stabilize spacecraft into a near-circular 2-hour orbit. Transition was designed to deliver MRO with a series of maneuvers into PSO. The MRO spacecraft then underwent a series of final checkouts prior to commencing primary science operations.

5. **PSP**: The spacecraft began its PSP, during which it conducted high-resolution imaging, atmospheric studies, and mineralogical mapping. The MRO is capable of performing off-nadir rolls of up to 30° for targeted observations and executes routine orbit maneuvers to maintain precision. Onboard logic uses the latest ephemerides and an Integrated Target List (ITL), i.e. a list of targets on Mars on which to perform either sequential or concurrent observations.

6. **Relay Phase (RP)**: The MRO has served as a crucial relay asset for multiple Mars missions, including Phoenix, Curiosity, Perseverance, and InSight. It has assisted during Entry, Descent, and Landing (EDL) by recording telemetry data via its Ultra High Frequency (UHF) antenna, Electra Proximity Link Payload (Electra), and performed orbital maneuvers to optimize coverage. MRO has functioned as a key communication relay, ensuring reliable data transmission between landers and Earth.

7. **Extended Mission**: After completing PSP and RP, the MRO entered the Extended Mission Phase. During this time, it continues to monitor the Martian surface, atmosphere, and climate, and assist future missions by acting as a communication relay.

6 ConOps and Functionalities

The chart below demonstrates clearer understanding of the ConOps and their relationships with the mission phases [3][7]:

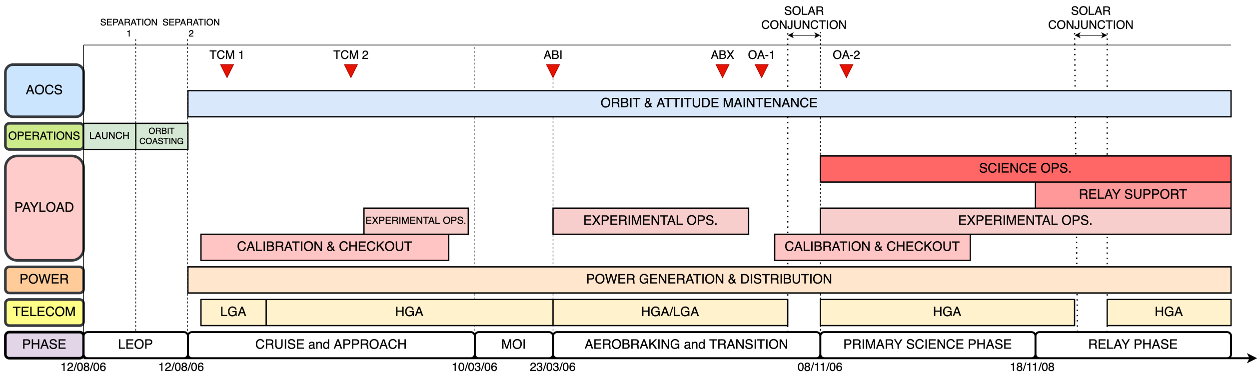

Figure 2: ConOps and phases of the MRO mission (not for scale).

7 Mission/System Level Requirements

The main requirements [1] at mission level can be grouped into:

- **Science Operations and Planning**: The orbiter shall operate in the primary science orbit for one Mars year, utilizing all six science P/Ls in targeting, survey, and mapping modes. It shall also conduct gravity and accelerometer investigations. The system shall support simultaneous operations and data acquisition by all science instruments. Additionally, a target acquisition selection process shall be created to ensure conflict-free targeting priorities.

- **Data Acquisition, Transmission and Storage**: The mission shall return a total science data volume of 34 terabits or more, over the one-Mars-year primary science phase, to achieve full mission success, with a minimum success criterion of 26 terabits [7]. At least 95% of acquired data shall be provided to spacecraft operators and science investigators. The system shall have the capability to properly manipulate and analyze data coming from scientific investigations and the Electra relay payload. Science downlink data rates shall support up to 6 Mb/sec, and the spacecraft shall provide onboard storage for at least 100 Gb of science-related data.

- **Navigation and Orbital Control**: The orbiter's position and velocity relative to Mars shall be predicted with an accuracy of 1.5 km in the downtrack direction, 0.05 km in the cross-track direction, and 0.04 km in the radial direction. The Navigation System shall ensure that, after MOI , the periapsis altitude remains within 200-400 km for at least 8 consecutive orbits without additional maneuvers. The spacecraft shall be capable of pointing anywhere within a ±30° cone about the nadir direction in the PSO. The orbit shall be near circular, at a low altitude, and near polar to allow for detailed imaging, complete coverage of the Mars surface, and a repetition of possible targets every 17 days.

- **Structural, Thermal and Power**: The spacecraft shall incorporate thermal protection and dissipation solutions to withstand the increases in temperature caused by aerobraking and the heat generated by multiple electric P/Ls and subsystems operating simultaneously. The structural design shall be able to withstand the torques and forces experienced during launch and aerobraking, especially on the joints of the appendixes [5]. The power system shall be able to supply the required electrical power to all P/Ls and instruments operating in parallel.

- **Mission Lifetime**: The mission shall ensure a minimum operational lifetime of one Mars year for the science payloads. The telecommunication instruments, including Electra and the High-Gain Antenna (HGA), should remain operational until 2009. Additionally, the spacecraft shall carry enough fuel to support operations until 2010 [7].

8 Payload

8.1 Scientific Instruments Overview

The instruments on the MRO include six main scientific payloads, as well as communication systems to support the mission's objectives of studying the Martian surface, atmosphere, and subsurface, while ensuring high rates of data downlink, uplink, and on-board handling [4].

- **High Resolution Imaging Science Experiment (HiRISE)**: It is a high-resolution nadir pointing telescopic camera with a primary mirror diameter of 50 cm and a 1.15° Field-of-view (FOV) [6]. It allows to obtain images of a vast area of the planet while being able to see details on the surface. Near-infrared observations provide an unprecedented view of layered materials, channels and geological formations in general. Among other duties, HiRISE also allows to identify appropriate landing sites for future Mars missions [4].

- **Compact Reconnaissance Imaging Spectrometer for Mars (CRISM)**: This spectrometer has a telescope of 10 cm with a 2° FOV and a maximal resolution of 18 m/pixel over a swath of 11 km by using its articulated mechanism to slow the apparent speed of image on the ground [6]. The CRISM uses infrared and visible spectrometers to detect certain minerals on the surface that indicate water has been present. It also acquires data for atmospheric survey.

- **Mars Climate Sounder (MCS)**: It is a spectrometer made up of two telescopes, each with a 4 cm aperture, mounted on a yoke frame that can move to autonomously adjust its pointing direction [6]. The instrument can measure temperature, humidity and dust content, and observe the atmosphere both visible and infrared light. The profiles generated are useful to predict Martian weather and climate, as well as improve understanding of the variations of the polar caps.

- **Mars Color Imager (MARCI)**: It consists of two framing cameras, one with two spectral channels in the UV band and the other with five channels in the visible band. MARCI produces a global weather map of the planet to obtain a view of daily, seasonal and year variations as well as atmospheric events like dust storms.

- **Context Camera (CTX)**: It is composed by a mono-chromatic camera working in a single wavelength band for visible light. It is mainly used to provide a background view of the terrain around smaller targets for interpreting the high-resolution observations captured by other instruments, such as HiRISE or CRISM .
- **Shallow Subsurface Radar (SHARAD)**: It is a nadir-looking synthetic aperture radar sounder designed to probe beneath the Martian surface to a depth of up to 1 km. SHARAD plays a key role in the research of water traces, scanning the subsurface in search of strong radar returns which suggest the presence of underground liquid or frozen water with a resolution of between 0.3 km and 3 km and the vertical resolution is approximately 15 m.
- **Additional Payload**: The mission includes a relay telecommunications package and two technology demonstrations [7]. The Ka-band system compares Ka and X-band, showing that Ka-band requires less power to transmit the same amount of data [4]. Electra, a UHF package, improves the landing precision of landers, aids the location of the rover, and provides a relay on the Mars network [4]. The Optical Navigation Camera (ONC) tracks Mars moons, refines moon ephemerides, and supports precise entry trajectories for landers [6].

Figure 3 shows the placement of the P/L in the spacecraft:

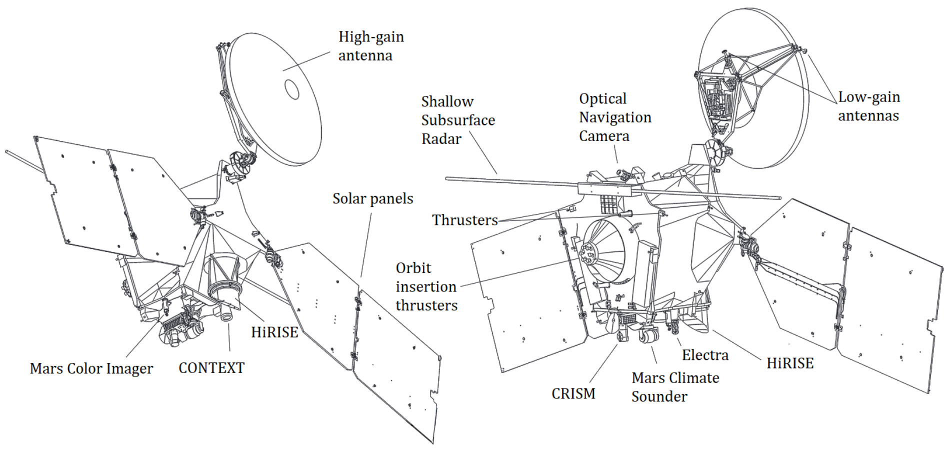

Figure 3: Components of Mars Reconnaissance Orbiter [6]

8.2 Additional Science Experiments

During its lifetime, the spacecraft itself (without additional payloads) was used to study the atmosphere and the gravitational field of Mars. In the aerobraking phase, accelerometer data was used to determine atmospheric density at different altitudes. The Doppler shift in the radio communication signal was used to study the gravitational field of Mars.

8.3 Payload - Phases, functions and objectives correlation

Table 1 highlights the correlation between the payload functions, the mission objectives listed in section 2, and the phases in which they have been involved. It can be noticed that some P/Ls have been used in multiple phases to achieve goals different from their main one. Apart from calibration and testing operations, which were primarily scheduled during the cruise phase and just before the PSP, imaging P/Ls were used to properly prepare for the aerobraking phase, while the MCS was used to retrieve information about the atmosphere during aerobraking.

Payload	**Payload Functions**	**Mission Objectives**	**Phase**
HiRISE	High Resolution Near-IR & Visible Imaging	To study active surface processes and landscape evolution	MOI , PSP, RP
CRISM	Spectrometric Surface & Atmospheric Analysis	To search for the residue of minerals that form in the presence of water	PSP, RP
MCS	Atmospheric Observation by Composition and Temperature	To observe the temperature, humidity, and dust content of the Martian atmosphere, making measurements that show variations in Mars' current weather and climate	ATP, PSP, RP
MARCI	Surface & Weather Mapping	To produce a global weather map of Mars to help characterize daily, seasonal, and year-to-year variations in the red planet's climate	MOI , PSP, RP
CTX	Wide & Context Imaging	To help provide a context for high-resolution analysis of key spots on Mars provided by HiRISE and CRISM	MOI , PSP, RP
SHARAD	Scanning of Mars Subsurface Composition	To look for indications of liquid or frozen water up to 1 km into Mars' crust	PSP, RP
Ka-band System	High-Rate Data Transmission Experiment	To provide information to improve performance in deep space communications	PSP, RP
Electra	Functions as a Node in the Mars Network	To provide relay communications for crafts on and around Mars	RP
ONC	Optical Tracking	To improve navigation capability, to identify microsatellites in Mars equatorial plane, to improve landing accuracy of rovers and landers	CAP, PSP, RP

Table 1: The payload functions and mission objectives of MRO.

9 Mission Analysis

For the mission profile selected, the launch period spanned four weeks, beginning from 10 August 2005, with a minimum launch window of 90 minutes each day. Of the initial four Trajectory Correction Maneuvers (TCMs) and two contingency maneuvers (to be executed in the event of a Mars-impact trajectory), ultimately, only two TCMs were required to reach target orbit at Mars. After aerobraking, the MRO was inserted into a low-altitude (250 X 315 km), near-circular, near-polar (92.65°) and frozen orbit with its periapsis fixed over the south pole. The choice of a nearly polar orbit ensures complete coverage of Mars over many orbits, while the altitude and near-circularity allow to obtain an acceptable trade-off between low drag effects and high-quality imaging. The choice of altitude was chosen to yield a repeating ground track such that nearly all locations on the planet can be viewed within 17 days by pointing the spacecraft off-nadir by up to 20° [7].

References

[1] Glen Havens. "Systems Engineering Challenges on Mars Reconnaissance Orbiter Mission". In: *AIAA SPACE 2007 Conference & Exposition*. DOI: `10.2514/6.2007-6091`. eprint: `https://arc.aiaa.org/doi/pdf/10.2514/6.2007-6091`. URL: `https://arc.aiaa.org/doi/abs/10.2514/6.2007-6091`.

[2] Ben Jai et al. "An Overview of Mars Reconnaissance Orbiter Mission, and Operations Challenges". In: June 2007. DOI: `10.2514/6.2007-6090`. URL: `https://doi.org/10.2514/6.2007-6090`.

[3] D. Johnston et al. "The Mars Reconnaissance Orbiter Mission". In: vol. 1. Feb. 2003, 1–204 vol.1. ISBN: 0-7803-7651-X. DOI: `10.1109/AERO.2003.1235052`.

[4] NASA. *Mars Reconnaissance Orbiter Official Page*. [Accessed: 14-Mar-2025]. 2024. URL: `https://mars.nasa.gov/mro/`.

[5] NASA Jet Propulsion Laboratory. *Global Surveyor Solar Panel Will Not Hinder Mission Goals*. [Accessed: 14-Mar-2025]. 1996. URL: `https://www.jpl.nasa.gov/news/global-surveyor-solar-panel-will-not-hinder-mission-goals/`.

[6] NASA Jet Propulsion Laboratory. *Mars Reconnaissance Orbiter Arrival Press Kit*. [Accessed: 14-Mar-2025]. 2006. URL: `https://www.jpl.nasa.gov/news/press_kits/mro-arrival.pdf`.

[7] Richard W. Zurek and Suzanne E. Smrekar. "An overview of the Mars Reconnaissance Orbiter (MRO) science mission". In: *Journal of Geophysical Research: Planets* 112.E5 (2007). DOI: `https://doi.org/10.1029/2006JE002701`. eprint: `https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2006JE002701`. URL: `https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2006JE002701`.

Acronyms

ATP Aerobraking and Transition Phase. 2

CAP Cruise and Approach Phase. 2, 6

CRISM Compact Reconnaissance Imaging Spectrometer for Mars. 4–6

CTX Context Camera. 5, 6

EDL Entry, Descent, and Landing. 3

Electra Electra Proximity Link Payload. 3–6

FOV Field-of-view. 4

HGA High-Gain Antenna. 4

HiRISE High Resolution Imaging Science Experiment. 4–6

ITL Integrated Target List. 2

LEOP Launch and Early Orbit Phase. 2

MARCI Mars Color Imager. 4, 6

MCS Mars Climate Sounder. 4–6

MOI Mars Orbit Insertion. 2, 4, 6

MRO mars Reconnaissance Orbiter. 1–4, 6

ONC Optical Navigation Camera. 5

P/L payload. 1, 3–5

PSO Primary Science Orbit. 1, 2, 4

PSP Primary Science Phase. 1–3, 5, 6

RP Relay Phase. 3, 6

S/C spacecraft. 1

SHARAD Shallow Subsurface Radar. 5, 6

TCM Trajectory Correction Maneuver. 6

UHF Ultra High Frequency. 3, 5