CDF STUDY REPORT
MarsFAST

Assessment of an ESA Fast Mobility Mars Rover

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Assessment of an ESA Fast Mobility Mars Rover

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FRONT COVER

Study Logo showing SkyCrane delivering a
Rover to the Mars Surface

STUDY TEAM

This study was performed in the ESTEC Concurrent Design Facility (CDF) by the following interdisciplinary team:

TEAM LEADER			
COMMUNICATIONS		POWER	
CONFIGURATION		PROGRAMMATICS/ AIV	
COST		RISK	
DATA HANDLING		MISSION ANALYSIS	
GS&OPS		STRUCTURES	
ROBOTICS		SYSTEMS	
MECHANISMS		THERMAL	
PAYLOAD			

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1 INTRODUCTION

1.1 Background

Following a recent ESA-NASA bilateral agreement, a mutual interest has been expressed to reinvigorate collaboration of the 2 agencies on Mars exploration, by investigating joint (ESA/JPL) missions to Mars post 2020, with a target launch date of 2024.

In this framework, the ESA Mars Robotic Exploration Preparation (MREP) program is now exploring the possibility for Europe to contribute to a mission with NASA reusing the Sky-crane concept, following the successful landing of NASA MSL mission. The European contribution will mainly consist of a surface element, the MarsFAST rover, able to demonstrate European fast and autonomous mobility technologies.

The MarsFAST rover study has been requested by the ESA Science Directorate (SRE-FMP) and financed as part of the General Studies Program. MarsFAST is a "fast" mobile and autonomous 150 kg class rover which represents a building block for the potential Mars Sample Return (MSR) mission, as well as providing in-situ science in support to future Mars robotic exploration.

The CDF study consisted of 9 sessions, starting with a kick-off on the 3rd of September 2014 and ending with an Internal Final Presentation on the 6th of October 2014. The study was carried out by a multidisciplinary team of experts from ESOC, ECSAT and ESTEC, and with the technical support of engineers from JPL/Caltech regarding the platform design and Rover/Platform interfaces.

1.2 Scope

"FAST", in the MSR scenario context, means mobility performance and capabilities of a rover which is designed to traverse at least **15 km** (straight line, i.e. actual accumulated ground track distance is higher) on a mission operations timeline of maximum 110 sols, without the support of radioisotopic material for either power generation or thermal control.

1.2.1 NASA/ESA Interface

The ESA MarsFAST rover is transported to Mars on a NASA pallet, provided by JPL, which is lowered onto the surface via the Sky-Crane Entry Descent and Landing System.

Most of the pallet surface is reserved for other NASA element(s), e.g. static platform, MAV technology demonstrator, etc. (which are not subject of this CDF exercise), with a portion of the pallet reserved for the ESA MarsFAST rover.

The objective of the CDF study is to carry out a conceptual design and assess the feasibility of a 150 kg-class rovers compliant with MSR FAST mobility performance requirements and able to provide in-situ science for supporting future Mars robotic exploration.

1.3 Document Structure

The layout of the report can be seen in the Table of Contents. The Executive Summary chapter provides an overview of the study and its major outcomes, and the details of each domain of expertise is covered in specific chapters within the report.

Due to the different distribution requirements, only cost assumptions, excluding figures are given in this report. Detailed cost estimates are provided in a separate document.

2 EXECUTIVE SUMMARY

2.1 Study Flow

Requested by the ESA Science Directorate and funded by the General Studies Programme (GSP), the MarsFAST CDF study was carried out in 9 concurrent sessions starting with a kick-off on the 3rd September 2014 and ending with an Internal Final Presentation (IFP) on 6th October 2014. The interdisciplinary CDF team consisted of specialists from ESA-ESTEC (NL), ESA-ESOC (DE), and ESA-ECSAT (UK). Part of this work was done at JPL/Caltech under contract with NASA.

2.2 Mission Objectives, Requirements and Design Drivers

The MarsFAST mission has the following mission objectives:

- Demonstrate MSR required mobility and autonomy capabilities (FAST)
- Define, accommodate, carry and operate a science payload that would at least allow:
  - Remote science → mast
  - In-situ science → robotic arm
  - Sample acquisition, transfer and analysis → robotic arm + “laboratory”.

The following high level mission requirements were derived:

- Compliance with the volume and mass allocated by JPL
  - Total mass of 200kg including system margins, HDRM & egress system
  - Total volume of 1.48x0.95x0.55m^3 (LxWxH or WxLxH)
- Demonstration of MSR required mobility and autonomy capabilities (FAST)
  - Traverse at least 15km (goal of 20km) straight line distance in a maximum of 110sols w/o nuclear power energy sources
- Definition, accommodation and operation of a science payload that would at least allow:
  - Remote science → mast
  - In-situ science → robotic arm
  - Sample acquisition, transfer and analysis → robotic arm + “laboratory”
- Reference mission scenario launch date 2024:
  - Assess compatibility with other launch dates up to 2034.
- Operate at a landing site range between 5deg South to 20deg North
- Communications:
  - Relay orbiter in UHF + Direct-to-Earth for basic / contingency telemetry.

The following design drivers were identified:

- Fast and long distance mobility
- Heating power required, especially in absence of RHUs
- Limited mass and volume available on pallet

- Implications of Direct-to-Earth capabilities on accommodation (antenna) and energy budget
- Hibernation during local dust storms(optical depth of 2) lasting up to 14 sols.

2.3 MarsFAST Mission Architecture

The key characteristics of the Mars FAST mission are provided in Table 2-1.

MarsFAST Mission Characteristics		
Programmatics	Launch date	October 2024
	Arrival date	September 2025
	TRL	At least TRL 6 (new ISO scale) at start of phase B2
	Model philosophy	STM + Locomotion BB + ATB + EQM + PFM + Spares
	Design lifetime	180 sols on Martian surface
	Planetary Protection	Category IVa requirements apply
Launch Segment	Launcher	Atlas V
	Launch site	KSC Cape Canaveral Air Force Station Eastern Test Range (CCAFS/ETR)
Space Segment	Landing platform	Mars Science Laboratory (MSL) Entry, Descent, and Landing (EDL) system (Sky Crane concept) provided by NASA/JPL
	Data relay orbiter	TBD
	Mars rover	MarsFAST rover (see Table 2-2)
	Egress system	MarsFAST egress system (see Table 2-2)
Ground Segment	Ground stations	Three ESA 35 m Deep Space Antennas (New Norcia, Malargüe, Cebreros) for DTE during surface operations No ESA ground station coverage before surface operations
	Mission operations	MOC at ESOC
	Science operations	Early surface operations phases: MOC and SOC integrated at ESOC For later phases: remote access for the mission scientists

Table 2-1: MarsFAST mission characteristics

The MarsFAST mission consists of two elements under ESA responsibility: the rover and the egress system. Both ESA elements are transported to Mars on a platform, provided by NASA/JPL, which is lowered to the surface using the Sky-Crane Descent and Landing System.

After landing, the ESA egress system has to ensure smooth and safe exit for the rover from the platform. Following the egress, the rover's mission is to demonstrate the fast roving capability as well as to conduct meaningful science operations to support future robotic exploration of Mars. In Figure 2-1, the planned sequence of sols is depicted for the entire mission lifetime of 180 sols.

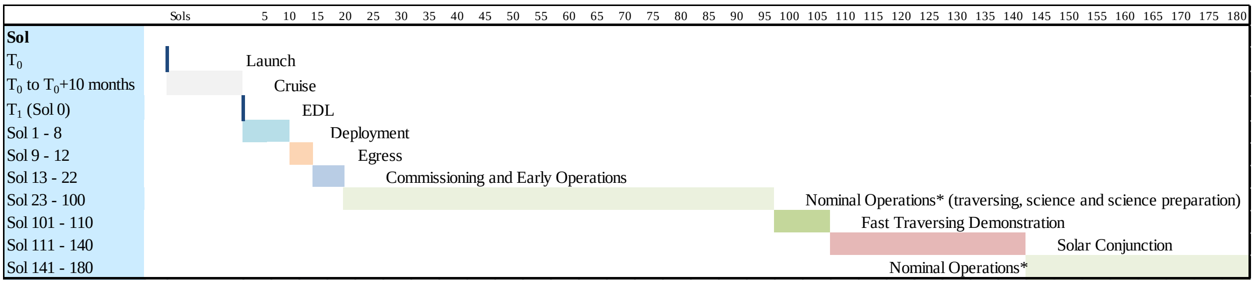


Figure 2-1: Mission lifetime sol sequence for the MarsFAST mission reference scenario (i.e. arrival in Sep 2025, Ls 133)

* Note: Local dust storms could occur at any time during the MarsFAST surface lifetime. This reference timeline assumes a contingency allocation of 14 sols (i.e. MarsFAST hibernation mode) at any time during Nominal Operations. Should a local dust storm happen at any other surface mission phase (e.g. Deployment, Egress, Commissioning and Early Operations), the mission timeline can be adjusted accordingly.

Besides the allocation for local dust storms, a 20% margin (19 sols) for operational contingencies is also included within the total of 118 sols Nominal Operations.

2.4 MarsFAST System Characteristics

The MarsFAST rover and the egress system are depicted in deployed configuration in Figure 2-2. The main characteristics of the rover as well as the egress system are listed in Table 2-2.

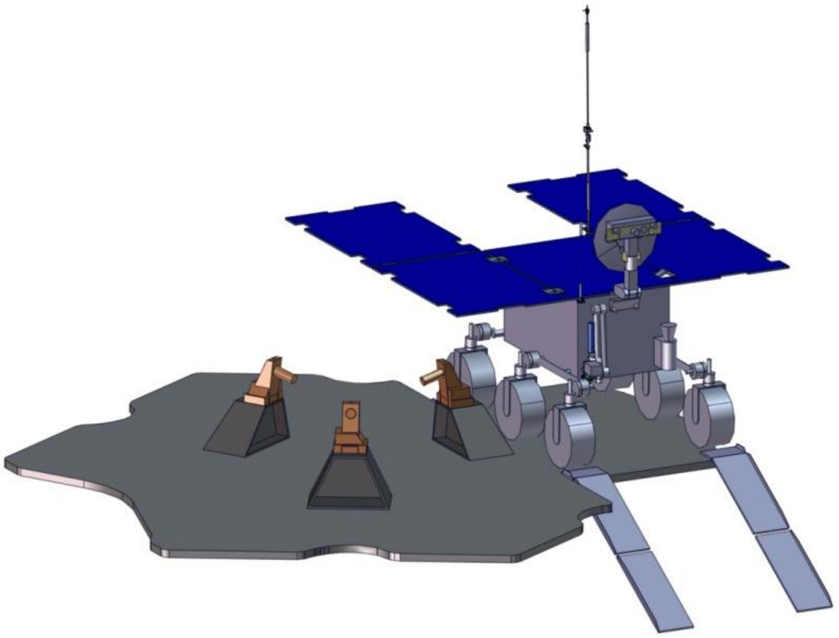


Figure 2-2: MarsFAST rover and egress system in deployed configuration

MarsFAST Rover Characteristics		
Mass	Payload	15.3 kg science payload
	Total	156.1 kg incl. 20 % system margin
Dimensions	Stowed	1159 mm x 530 mm x 910 mm
	Deployed	2309 mm x 1244 mm x 1815 mm
Structure	Composite sandwich moulding with CFRP faceskins and glass fibre reinforced plastic (GFRP) honeycomb core	
Mechanisms	HDRMs as required to fix appendixes (locomotion subsystem, mast for camera head and HGA, solar array and robotic arm) and body to the rover platform	
	Camera head and high gain antenna (HGA) are mounted – facing opposite directions – on a pan and tilt mechanism at the top of a short deployable mast	
	Actively controlled Solar Array Deployment Mechanisms	
	Corer / Grinder for the Attenuated Total Reflection spectrometer on the tip of the robotic arm	
Robotics	Locomotion Subsystem 6x6x6	6 rigid wheels: 30 cm diameter, 13 cm width
		2 side bogies plus 1 rear bogie 3 passive joints for stabilisation when traversing 3 motorised joints per wheel for deployment, driving

		and steering
		36 motion controllers in the warm box
	Robotic Arm	4DoF, 450 mm reachable sampling radius and compact stowed configuration achieved through 2 limbs and 4 joints
GNC	2 Navigation Cameras on the camera head on top of short mast at 1.1 m	
	2 Localisation Cameras on the front rover body	
	2 IMUs	
	1 Sun Sensor	
	1 Hazard Camera on the rear rover body	
	Limited autonomous navigation capability (SPARTAN) on dedicated FPGA (see Data Handling equipment)	
Power	Solar Array	2 deployable wings (2 panels each) and 1 body mounted solar panel Total solar panel area: 2.24 m^2 Solar cells: 3G30 (baseline) No dust removal system Average energy: 607Wh/m^2 per Sol
	Battery	7s12p, Li-ion cells: 18650 NL 653Wh EOL 4.8 kg
	PCU	Unregulated bus architecture, MPPT
Communications	2 Dual UHF/X-Band Transponder	
	2 Travelling Wave Tube Amplifiers, 65 W RF output power	
	2 UHF low gain antenna, $\lambda/4$ monopole	
	1 metasurface X-band high gain antenna, 35 cm diameter	
	1 Radio Frequency Distribution Unit	
Data Handling	Single centralised unit implementing all C&DH functionality - Hot redundant power conversion module, on-board timer, safeguard memory, reconfiguration module and telecommand decoder - Cold redundant processor module, IO modules, mass memory modules and telemetry encoders - Non redundant navigation processing HW, consisting of a co-processor and a dedicated ASIC/FPGA	
Thermal	Insulation on internal rover bathtub walls and around battery: 3 cm Aerogel (baseline), gas gap (option) Heaters to maintain the units within the allowable temperatures	

	Remove of excess heat during operations using loop heat pipes and radiators	
Instruments	Panoramic Stereoscopic Camera and 1 High Resolution Camera mounted on a Mast	
	Close-up Imager mounted on Robotic Arm	
	Optically Stimulated Luminescence Dating Instrument	
	Mössbauer and X-Ray Fluorescence Spectrometer	
	Attenuated Total Reflection Spectroscope	
	Meteorological Package on Deployable Boom	
	MarsFAST Egress System Characteristics	
Egress System Mass	Dry mass	18.23 kg
	Total	21.87 kg incl. 20% system margin
Mechanisms	Egress ramps, spring actuated hinges and HDRMs	

Table 2-2: MarsFAST System Characteristics

2.5 Technical Conclusions

The study concluded in a feasible mission design concept compatible with the mission objectives and the requirements. This report presents the main trade-offs and design outcome.

Note that the initial mass allocations were 150 kg for the rover and 50 kg for the egress system. Despite the rover mass slightly exceeding its allocation, the total mass of 178 kg is below the total 200kg JPL mass allocation.

The requirements were satisfied with the following exceptions and limitations:

- The presented design allows for a verification of the fast roving capability of the rover without completing the overall distance required for the MSR mission. In favour of increasing the science output, the time for mere fast roving was limited to a verification period.
- The current design ensures survival in hibernation mode in worst case conditions for only 12 days, instead of 14. Since these conditions occurat the end of the designed rover lifetime (i.e. solar panels with lowest efficiency due to accumulated dust) and worst case latitude loss of the rover due to a local dust storm at this time was considered acceptable.
- Only limited DTE communication will be possible due to the power limitations. Transmitting the science data to Earth in a DTE only architecture requires favourable conditions (long illumination, low power consumption of other subsystems) to allocate enough energy to the transmission. In the worst case scenarios a DTE time of ore than 5 min. could not be realised.

3 MISSION OBJECTIVES

3.1 Background

Following ESA-NASA bilateral, a mutual interest has been expressed to reinvigorate ESA-NASA collaboration on Mars exploration, by investigating joint ESA/JPL missions to Mars post 2020 with a target launch date of 2024.

Within this framework, the ESA Mars Robotic Exploration Preparation (MREP) program is now exploring the possibility of Europe contributing as a junior partner in a single joint mission with NASA reusing the Sky-crane concept following the successful landing of NASA MSL. This contribution will be focused on one surface element i.e. a mobile surface platform (MarsFAST) in order to demonstrate European fast and autonomous mobility technologies in preparation for international collaboration in the potential Mars Sample Return (MSR) mission (e.g. provide a building block for MSR).

MarsFAST targets a FAST mobile and autonomous 150 kg class rover that would allow Europe to build on MSR technologies at the same time as providing in-situ science for supporting future Mars robotic exploration.

“FAST” in the MSR scenario context means mobility performance and capabilities of a rover which is designed to traverse at least 15 km straight line on a mission operations timeline of a maximum of 110sols without the support of radioisotopic material for either the power generation or thermal control.

The ESA MarsFAST rover is transported to Mars on a pallet provided by JPL, which is lowered onto the surface via the Sky-crane Entry Descent and Landing system.

A large fraction of the pallet is reserved for other NASA element(s) (e.g. static platform, MAV technology demonstrator, etc.) and it will not be part of this CDF.

A fraction of the pallet is reserved for the MarsFAST rover. Following JPL/NASA iterations, the first assumption for the allowable envelope and mass can be found in section 6.

3.2 Mission Objectives

The MarsFAST mission has the following mission objectives:

- Demonstrate MSR required mobility and autonomy capabilities (FAST)
- Accommodate, carry and operate a science payload that would at least allow:
  - Remote science → mast
  - In-situ science → robotic arm
  - Sample acquisition, transfer and analysis → robotic arm + “laboratory”

The mission requirements are specified in the system Chapter 7.1.

3.3 Study Objectives

The objective of this study is to design and evaluate the feasibility of 150 kg-class rovers compliant with MSR FAST mobility performance requirements and capable to provide meaningful science for supporting future Mars robotic exploration.

The main objectives of the study are the following:

- Detailed design of a rover to comply with the MarsFAST requirements by optimising / evolving the ESA current existing rover concepts: ExoMars, MarsREX (CDF study RD[9]) and MREP Sample Fetch Rover Industrial studies concepts.
  a) Identify the key design drivers and the operational challenges
  b) Review the European rover related technology developments state of art (e.g. MREP Technology development plan activities, flexible solar arrays, etc...)
  c) Trade-off different subsystem design options focusing on reliability (e.g. autonomy levels, dust removal systems, miniaturisation, single point failure strategy, mode management etc...)
- Propose and define a Science case and payload suite (i.e. only for reference, no Science Team is supporting the study) considering the MarsFAST capabilities that will allow as a minimum:
  - Remote science → mast
  - In-situ science → robotic arm
  - Sample acquisition, transfer and analysis → robotic arm + “laboratory”
  - Prioritised the model payload to assess the impact of a degraded science mission.
- Propose and define the verification&validation (V&V) strategy and its approach in order to comply with MSR FAST mobility and autonomy performance requirements and:
  a) Considering the mission science needs
  b) Operational constraints for the different launch dates from 2024 to 2034
  c) Analysing the optimal on-ground / flight sharing for the V&V approach
- Investigate the operational and interface requirements in order to demonstrate other potential MSR mission technologies demonstration by this mission, e.g.:
  a) Handover of cache onto the Mars Ascent Vehicle
  b) Inter-communications between landing platform and rover
  c) Efficient return of the rover to the MAV (smart path planning)
- Identify technology development needs and Programmatics & Cost (considering also the outcome of the V&V strategy and its approach

4 MISSION ANALYSIS

The mission analysis work for the MarsFAST study was limited to providing the environmental and station coverage data for the latitude range considered over the time frame of interest.

Only the surface phase resulting from transfers to Mars in the opportunities from 2024 to 2033 were considered. The resulting surface conditions for a latitude band from 5 deg S to 20 deg N have been studied. The results were provided to the other module experts as input for their respective work.

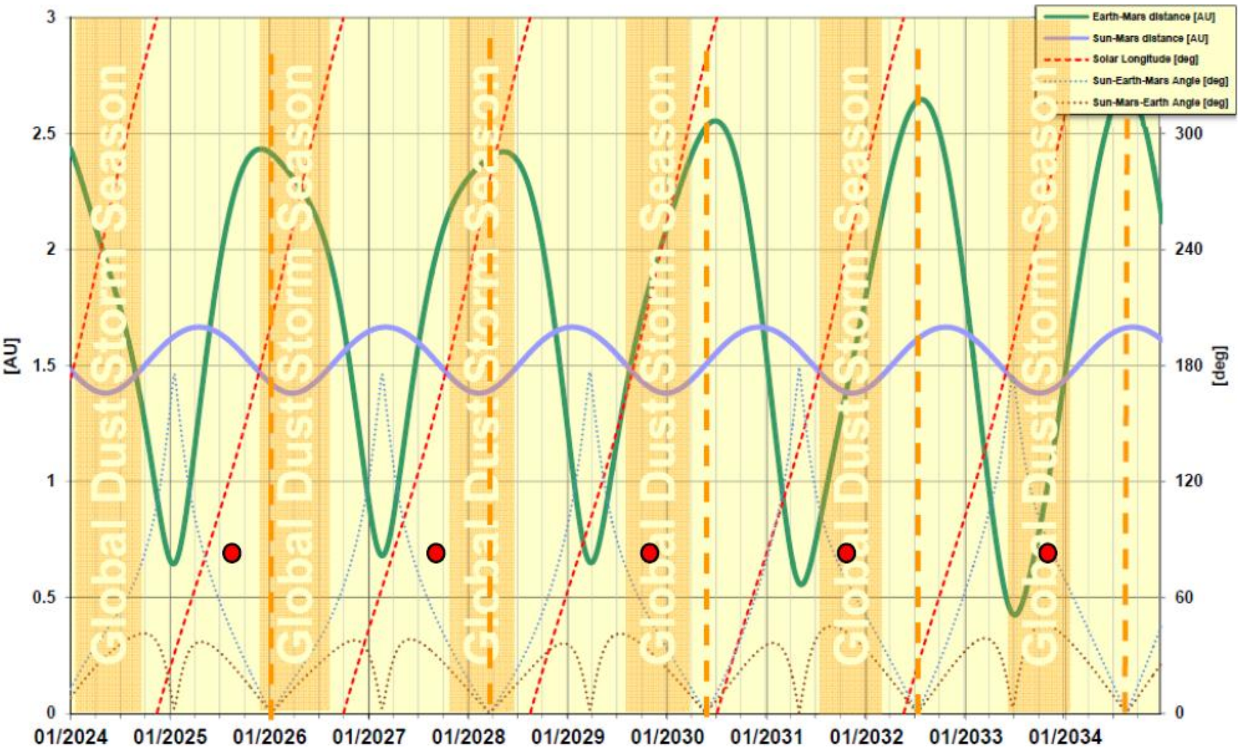


Figure 4-1: Mars Environmental Conditions 2024-2034

Figure 4-1 shows the distance from the Sun and from the Earth to Mars, the solar longitude, the placement of the global dust storm season (a phase of the Mars orbit where there is an increased statistical probability of an event that raises the dust content in the atmosphere regionally or globally- This probability is not constant throughout the phase, so the "global dust storm season" should be seen as a purely indicative concept) , the approximate arrival times for each of the five opportunities and the times of superior conjunction events.

4.1 Sun Illumination

The local solar time of sunrise and sunset is a function of the latitude of the surface location on Mars and of the season, which in turn depends on the date. From the sunrise/set times follows the number of daylight hours. The theoretically available solar energy per day is obtained by integrating the power arriving at a flat plate on the Mars surface over one sol, taking into account the sun elevation but not attenuation by atmospheric absorption or dust, which will further reduce the available power input. These need to be taken into account via appropriate models.

In all diagrams the solar longitude is included for reference. This clearly indicates the prevailing season on Mars. A solar longitude of zero is defined as vernal equinox or start of northern spring (southern autumn). As expected, the seasonal effects strongly increase with the distance of the surface location from the equator.

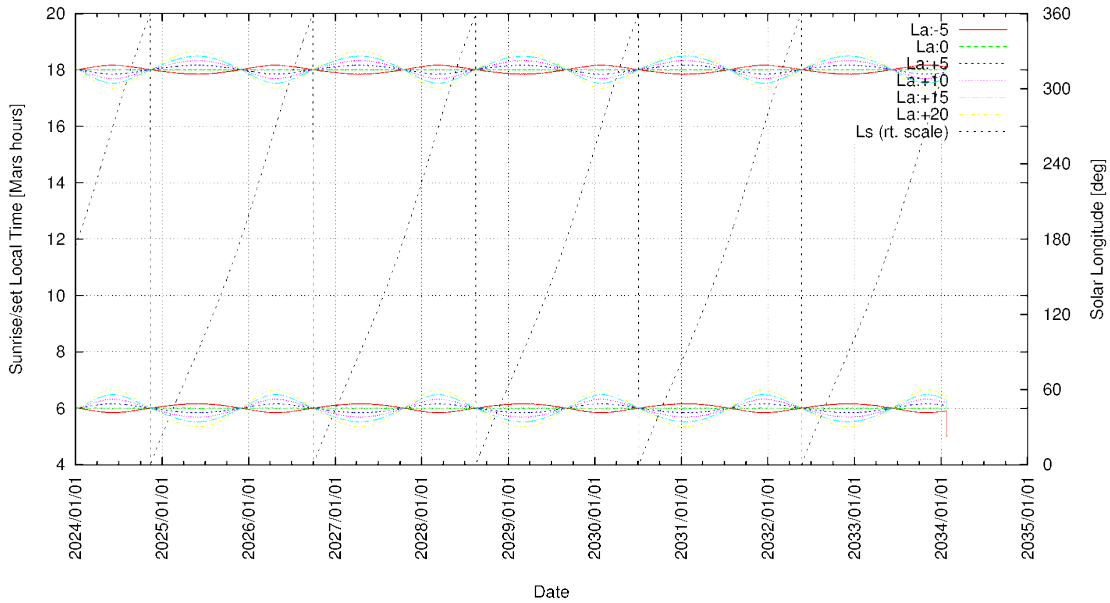


Figure 4-2: Sunrise/set Local Solar Time as Factor of Date and Latitude

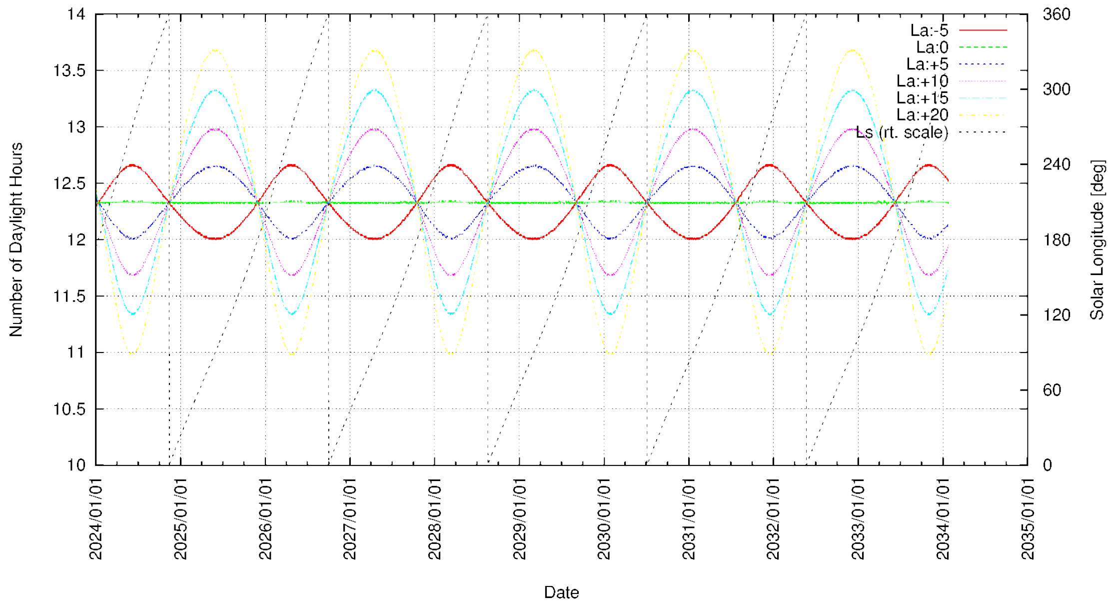


Figure 4-3: Earth Hours of Daily Sunlight over Date and Latitude

The amount of available solar energy follows from a superposition of various effects. A strong variation of the energy over each Mars year is a result of the eccentricity of the

Mars orbit. Its perihelion is crossed round a solar longitude of 255 deg, in late northern autumn.

There is an asymmetry between the northern and southern hemisphere, as can be seen by comparing the energy availability at 5 deg S and 5 deg N in Figure 4-4. southern winter coincides with high Sun distances, so the solar input is lower than in northern winter. Conversely, southern summer coincides with closer proximity to the Sun than northern summer.

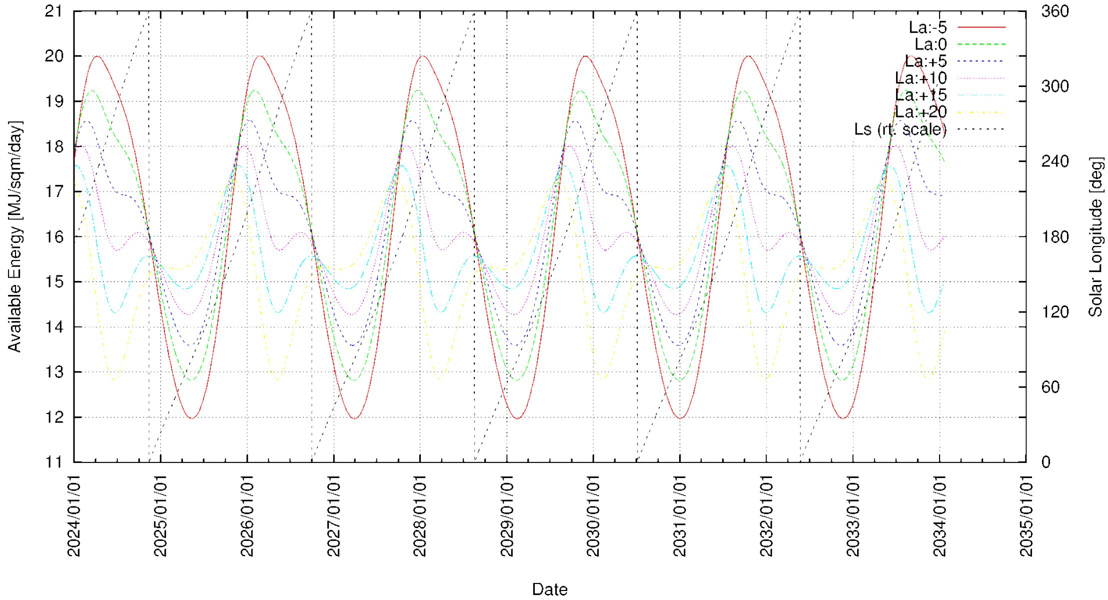


Figure 4-4: Available Daily Energy as Fct. Of Date and Latitude

4.2 Earth Visibility from the Mars Surface

The true local solar time at Earthrise/set as function of date and aerographic latitude is shown in Figure 4-5. The Earth visibility can show a significant offset with respect to the local day time. If communications are required to take place only when sufficient solar power is available, the Earth visibility constraint is combined with the solar elevation constraint. At certain periods, this significantly reduces the duration of the daily time slot available for communications. Additionally, the actual visibility of Mars from the ESTRACK ground stations above a given minimum elevation must be considered.

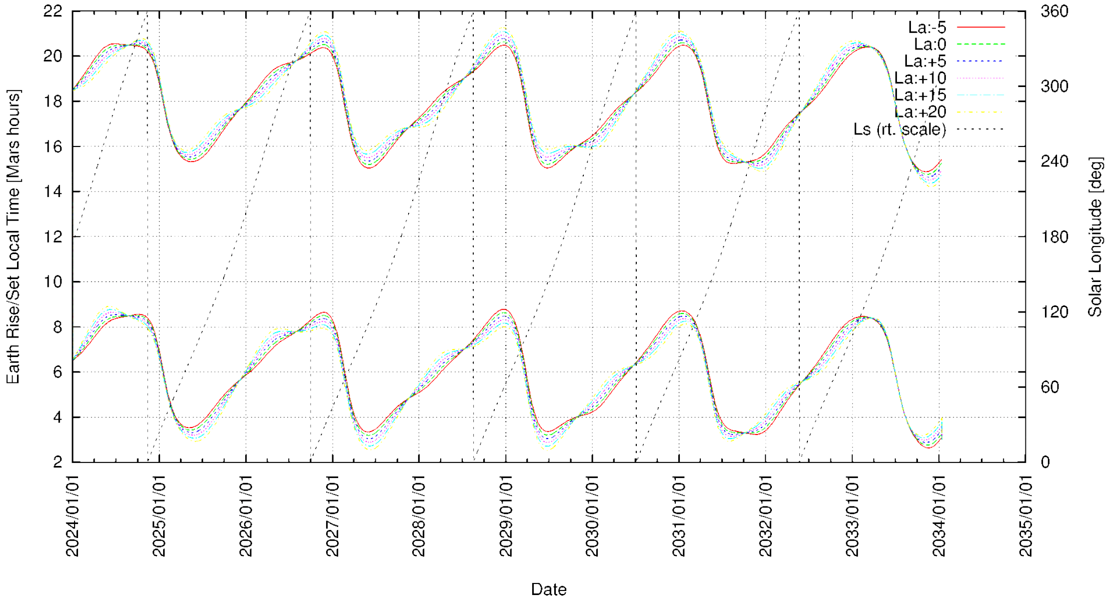


Figure 4-5: True Local Solar Time of Earthrise/set as Fct. of Date and Latitude

5 PAYLOAD

5.1 Requirements and Design Drivers

The scientific main topic of this mission addresses recent geologic surface and sub-surface transport processes on Mars. The term “recent” has to be seen in a geologic context and refers to a time interval between now and some 100,000 years ago.

The focus is on aeolic and fluviatile erosion and transportation of surface material. Thus sedimentary deposits like dunes and river beds are the main target for sample collection and analysis.

The investigation and understanding of such processes have a wider range of implications and application to the search for less-hostile environments for recent life, but also for the identification of possible deposits of fossil life. Further it completes the understanding of the current Martian environment, with implications for the identification of future landing sites for returning samples from Mars and eventually the preparation for human exploration. In particular, the choice of landing sites that provides a stable and sustainable outpost will benefit from a full understanding of the local environment and changes over a shorter time frame.

The technical demonstration goal of this mission, to cover a long distance drive within a few weeks only, supports the scientific goal to investigate multiple and different places at similar boundary (= weather) conditions. However, the possible requirement to enter “difficult” terrain like the edges of dune field or potentially soft old river beds must be carefully analysed and traded against the inherent risks.

5.2 Assumptions

The selected model payload is grouped into categories based on accommodation or specific system requirements. As such, each instrument stands as a placeholder for a specific instrument type. For example, a Moessbauer spectrometer that requires a deployment device and a fresh processed surface for a proper analysis could be replaced by some kind of close-up spectrometer that would have similar requirements.

In order to allow for proper mission study, each instrument group contains a “real” instrument that has significant heritage from a previous space missions or instrument development activities. These instrument resource budgets were applied during the course of the study and a feasible mission scenario has been developed. It was the intention to cover a large range of different instrumentation (and scientific disciplines) in order to study the different accommodation requirements and provide a flexible platform for any future studies.

5.3 Baseline Payload Complement

In Table 5-1 the chosen payload elements are grouped according to their deployment requirements. Each payload element is an example of its group and could be replaced by other type of instruments with a different scientific orientation.

Instrument	Measurement	Category
Stereo Camera & hi-res channel	• Overview, context and high resolution images • Local and regional geology • Navigation and operations	• Remote sensing (not strictly true for meteorological instruments) • Passive, directionless deployment by a mast • Possibly pointing device
Meteorological package (incl. boom)	• Wind speed, temperature, pressure, humidity, electric field, water, volatiles, sand counter, gas species	
Mössbauer spectrometer & X-ray fluorescence spectrometer	• Mineralogy of iron bearing minerals • Oxidations state • Bulk chemical composition of soil and rocks	• In-situ investigation • Active deployment by robotic arm • Accommodation in corer/grinder (ATR)
Attenuated Total Reflection Spectroscopy (ATR) & imager (sub-surface)	• Subsurface microscopic imaging • Mid-IR spectroscopy • Mineralogy, water and water ice detection	
Close-up imager	• Close-up and high resolution images of surface and sediments	
Optically Stimulated Luminescence Dating (OSL)	• Burial age of mineral grains	• In situ investigation • Requires sample preparation

Table 5-1: Categorisation of scientific payload

The chosen model payload complement covers a wide range of disciplines and delivers a sound and complete description, from regional geology to sub-surface microscopic observations. The suite of cameras covers, without any gap, the resolution required to observe the distant landscape and large landmarks, topographic features in close vicinity of the lander like rocks and soil and also the microscopic appearance of the subsurface soil. The panoramic imager, the high resolution camera, the close-up imager and eventually the sub-surface imager deliver full colour images of the chosen targets.

The mineralogy and chemical composition of soil and rocks previously described in the photographic documentation will be analysed by means of Mössbauer spectroscopy, mid-IR spectroscopy and x-ray fluorescence spectrometry.

Since the main targets are recent sedimentary deposits, the optically stimulated luminescence dating will determine the deposition age of the debris. The cause for surface transport and blanket coverage maybe fossil (or recent?) water flows and wind action carrying grains over larger distances.

The current climate and atmospheric characteristics will be fully described by the extensively equipped meteorological package. The data can be linked to the close-up observations of the soil and corresponding conclusion can be drawn. The recent coupling of the atmosphere to the soil can be made on a microscopic and macroscopic scale.

5.4 List of Equipment

In Table 5-2: the basic accommodation requirements and resources allocations of the various payload elements are listed. This data is based on instrument designs with either significant heritage from previous space missions or advanced breadboarding activities. No margins have been applied to the listed values.

	StereoCam	**HiResCam**	**Close-up imager**	**OSL**	**Mössbauer/ XRF**	**ATR**	**Meteo Pack**
	S/C interface						
accomm.	Rover mast	Rover mast	Robotic arm	Rover body	Robotic arm	In corer	Mast
electrical	28 V reg	28V reg	28V reg	28V reg	28V reg	28VC reg	28 V reg
data	Spacewire	Spacewire	Spacewire	--	--	--	--
thermal	--	--	--	--	--	--	--
	Pointing						
direction	mast rotation	mast rotation	arm position	funnel upright	arm position	Corer position	none
Field of view [°]	48 per unit	8.8	14.0	na	na	na	na
Unobstructed field of view [°]	180	180	180	na	na	na	na
	Physical						
No. of unit	2 camera 1 eboard	1	1	3	2	1	various
Volume (hxwxl) [mm]	79x43x75 head 160x100x15 e-board	168x50x50x	175x100x 125	OSL 140x120x180 e-boards (2x) 160x150x100	Head 90x50x40x e-board 80x50x15	Optical head 22x22x55 Electronics 22x22x90	50x80x 670
Mass [kg]	1.5	1.0	1.0	2.5	0.6	0.5	3.0
Mass +20%	1.8	1.2	1.2	3.0	0.72	0.6	3.6
	Power [W]						
Operations	10	10	10	12.0	8	3	8/6
Stand-by	6	10	3.3	8.0	6	1	2
	Temperature [C°]						
Min/max ops	-120/+50	-70/+40	-50/+60	-50/+60	-50/+60	-50/+60	tbd
Min/max non ops	-150/+50	100/+60	-50/+70	-50/+70	-50/+70	-50/+70	tbd
Eboard in box ops	-55/+50	--	--	-55/+50	-55/+50	--	--
TRL	4	4	4	4	4	4	4

Table 5-2: The payload elements and their basic characteristics and accommodation requirements, total payload mass allocation: 12.12 kg

5.4.1 Panoramic Camera and High Resolution Camera

The camera package combines two different systems. The panoramic stereoscopic camera contains a pair of identical wide-angle cameras (WAC) with a field of view (FoV) of 48 degree. The high resolution camera (HRC) with a FoV of 8.8 deg is designed for imaging specific features on the landscape. Both cameras will be mounted on a deployable mast and point in the same direction.

The resource budgets of both systems were taken from a relatively simple and lightweight design as was used for example on the Beagle2 lander. However, instead of a filter wheel a modern full colour APS like the Foveon X3 has been assumed.

The stereoscopic camera will be used to obtain overview images mapping the surrounding of the rover. Specific features can be imaged at higher resolution by the HiRes camera.

5.4.2 Close-Up Imager

The close-up imager is a variable focus camera covering the range from 10 mm up to infinity. The principle design is based on the CLUPI camera under preparation for the ExoMars missions and similar instrument proposals that have been made to other missions study concepts like MarcoPoloR, an ESA asteroid sample return mission.

The camera has a compact and light weight design. It will be mounted on the robotic arm for close inspection of the sampling side and other small areas of interest. The images provide a sub-mm resolution that bridges between performance of the large camera systems mounted on the rover’s mast and the micro camera located in the corer system.

5.4.3 Optically Stimulated Luminescence dating (OSL)

This type of dating technique determines the burial age of mineral grains, or in other words the age that reflects the duration when the grain has been exposed to the sun light for the last time. Sedimentary grains are buried by aeolic (wind) or fluviatile (water) processes on the surface of Mars. The burial age mirrors the surface dynamics and activities of the last 40 to 100,000 years. This limit is set by the methodology. Once a surface grain is buried it accumulates charges induced by the natural radiogenic environment and the external galactic cosmic ray background. However, there is a physical saturation limit which limit the dating period.

After collection of the sample material from a depth greater than 2 cm it must not be exposed to daylight. The UV component of the light would empty the charges relatively fast and destroy the contained information. The sample will be exposed to different laser sources at different wavelengths within the instrument. The release of charges creates photons that are analysed and their amount reflects the total dose accumulated after last exposure.

For a proper determination of the burial age the sample must be calibrated i.e. the efficiency of retaining charges is measured. This is done by irradiation by x-ray tube or an active beta source at a known induced dose. The here budgeted version (Figure 5-1) contains an x-ray tube.

For terrestrial applications the method is usually applied to quartz grains. Quartz is a mineral that hardly exists on Mars. A new analysis approach has been developed in order to use minerals that are more common in Martian rocks. One of the prime candidates is the mineral feldspar to which the analysis sequence had to be adapted. The successful application has been proven by dating of (quartz-free) terrestrial basalts. Basalts are commonly accepted analogues to many Martian rock types (RD[1], RD[2]).

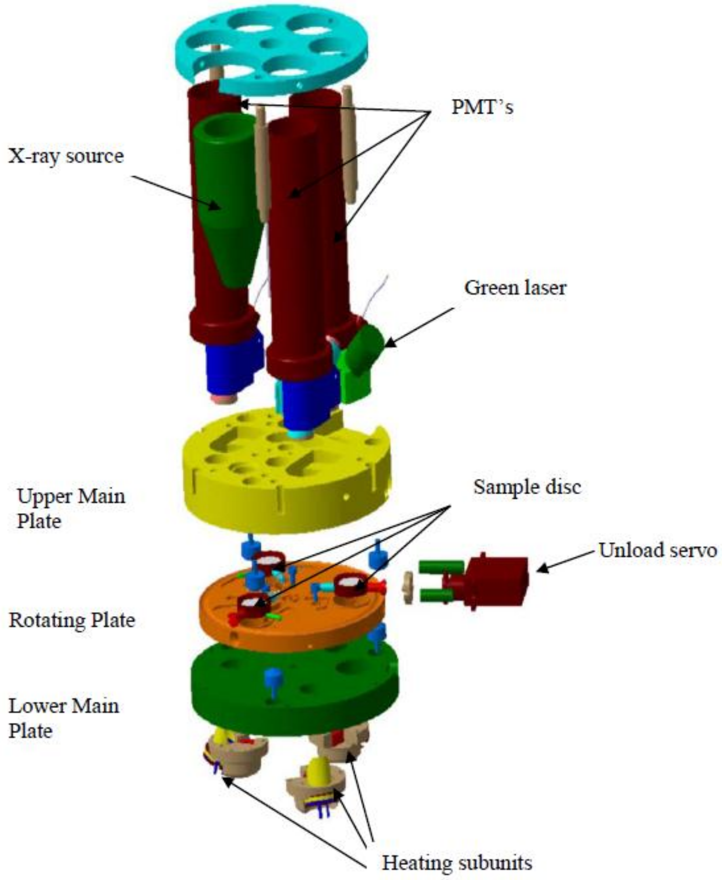


Figure 5-1: Breadboard design of the OSL instrument (re-print from RD[1])

5.4.4 Mössbauer Spectroscopy and X-Ray Fluorescence Spectrometry

Mössbauer spectroscopy is a method for in-situ detection and analysis of iron bearing minerals. The ratio of Fe^{2+} and Fe^{3+} ions in the analysed rock allows conclusion on its oxidation state. X-ray fluorescence spectrometry is used to measure the bulk chemical composition of the analysed rock.

Such an instrument has been successfully demonstrated on the MER missions to Mars. These instruments contained no x-ray channel for rock analysis. In later versions of the instrument due to an advanced sensor technology the x-rays can be analysed simultaneously to Mössbauer data acquisition and in addition the overall integration time for one measurement has been greatly reduced.

The sensor head shall be accommodated in the deployment device close to the corer and close-up camera. The deployment device at the tip of a robotic arm will dock the instrument against soil or a rock. The investigation would benefit from a grinder which removes the outermost weathered layer. The underlying fresh material will provide access to the original composition of that target.

5.4.5 Attenuated Total Reflection Spectrometer and Imager

Attenuated Total Reflection spectroscopy (ATR) is a specific type of infrared spectroscopy. Depending on the chosen wavelength range the mineralogy of the target material can be investigated. ATR is especially sensitive to water (ice) detection. Laboratory results have demonstrated that monolayers of water molecules adsorbed to a substrate can be detected.

The principle of ATR is based on an infrared beam that is reflected within the thickness of a window. The window is firmly pressed against the material under investigations. A small fraction of the light gets absorbed and the resulting output can be spectrally analysed and material specific absorption bands identified.

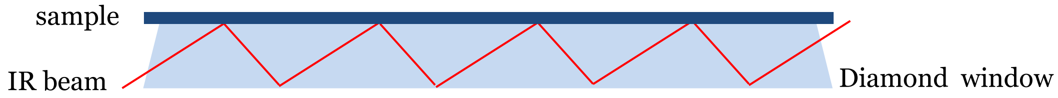


Figure 5-2: Principle of ATR measurements; IR beam in a total reflection geometry entering a window pressed against the sample material

The transparent window is also used by an imaging unit. An illumination set-up consisting of 4 LEDs is used for sub-surface investigations.

The ATR imaging system was originally breadboarded for an application in a mole, a self-penetrating device for sub-surface investigations (RD[3]). Figure 5-3 shows the very compact design of the miniaturised instrument. In the present case the ATR shall be mounted inside the corer that gives unique access to the sub-surface material that will be later analysed in the OSL.

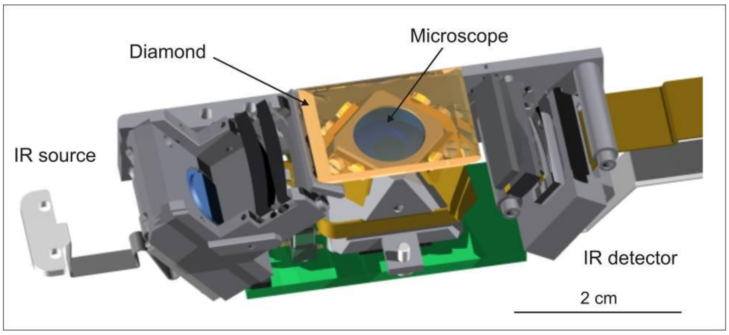


Figure 5-3: A very compact design of the ATR and microscopic imager (image reproduced from RD[3])

5.4.6 Meteorological Package

This version is based on the ExoMars Humboldt AEP (Advanced Environmental Package) proposal but adds an absorption spectrometer in order to fully characterise turbulence, and dust and volatile exchange processes. An almost identical P/L was also used in the ESA Mars Network Science Mission study concept (MNSM) in RD[5]. In this study the information on the instrumentation is reproduced to a large extent.

The payload consists of two units:

- Deployable 1.1 m boom, equipped with:
  - Air temperature sensors at four heights *
  - Ultrasonic 3-D wind sensor at top of mast *
  - Sand impact sensor *
  - Humidity sensor *
  - Electric field sensor *
  - Tunable Laser Spectrometer (TLS) near top of mast
- A central electronics unit, which includes pressure sensor *

Items marked with an asterisk are inherited directly from the ExoMars AEP / ARES payloads.

5.4.6.1 The atmospheric mast

The atmospheric mast (1.1 m deployable boom) specified here in this model payload is based on the ExoMars/AEP mast. The baseline is a 2-segment mast, of carbon-fibre reinforced polymer (CFRP) tube, driven by springs located in both the base and middle hinges. A lock / deployment mechanism is used to hold the mast in the deployed mechanism from AIV through launch, cruise and landing. The mechanism qualified for the ExoMars/AEP mast used a fuse wire (For deployment, this required 1.8 A from the unregulated power line of the lander (27-30 V) for 0.2 seconds). The mass allocated for the boom subsystem, of 1.6 kg, is sufficient to allow a motor-driven system instead of spring-driven system.

Figure 5-4: 2 segment boom without sensors as seen from the middle hinge end (left) and 2 segment boom deployment test (right)

For MarsFAST, the major change (with respect to the AEP mast design) is that a tunable laser spectrometer (0.5 kg mass) has been added to the top of the mast; this will require a significant increase in mass and volume of the mast, and will require minor re-organisation of the instrument layout on the mast. The proposed volume envelope is based on a 2-segment mast of AEP design. A larger volume and mass has been allocated for the ultrasonic anemometer, to provide better physical accommodation of the 3-D anemometer. The volume envelope in the stowed position is also taller than the AEP envelope, in order to accommodate the TLS.

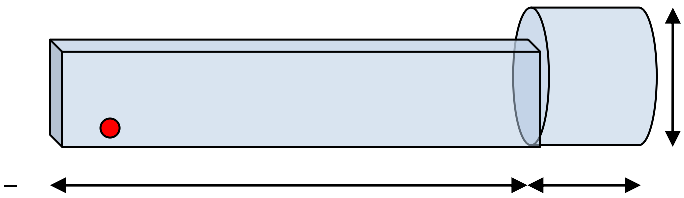


Figure 5-5: Proposed envelope for the stowed atmospheric instrument mast. Cylindrical volume is 120 mm Ø x 120 mm L. Rectangular volume is 50 mm W x 80 mm H x 550 mm L for a 2-segment boom. The red spot indicates the location of base hinge of mast when deployed.

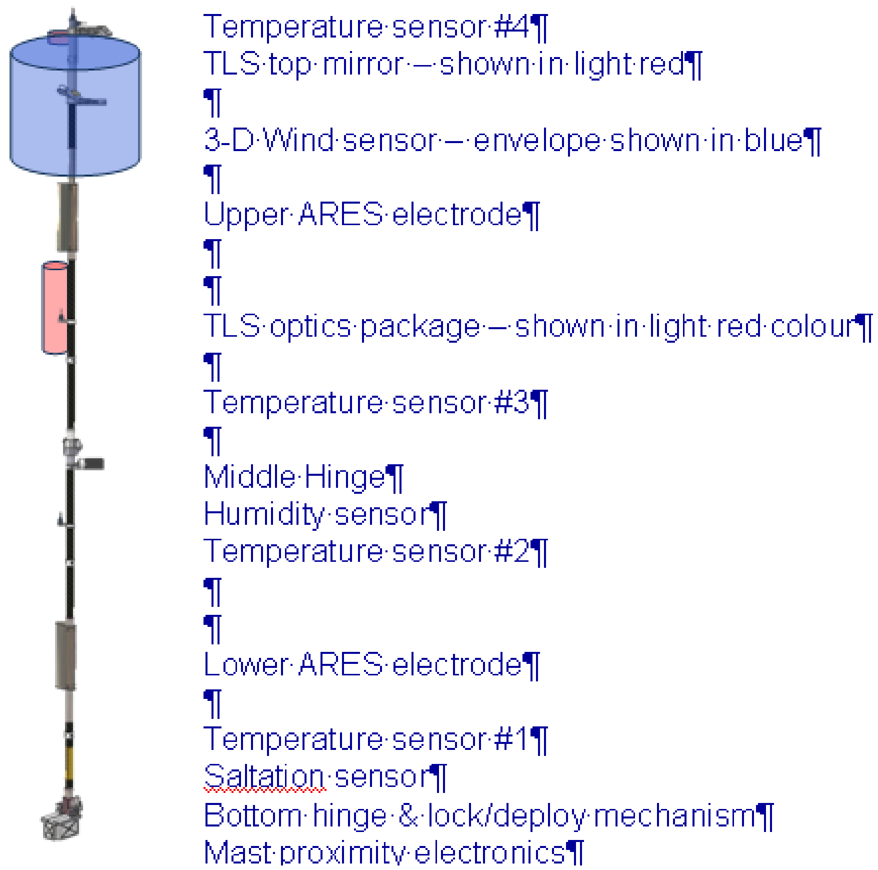


Figure 5-6: Deployed mast, the deployed volume is 120 mm Ø and 1.1 m high

There is a front-end electronics box at the base of the mast which includes pre-amps for the temperature and sand impact sensors, and for deployment mechanism. All electronics in this box can operate at Martian ambient temperatures.

5.4.6.2 Temperature sensors

The temperature sensors are thin-wire E-type thermocouples, following a design used on Mars Pathfinder, MVACS, Phoenix, and ExoMars AEP. Each temperature sensor consists of three individual thermocouple junctions supported on a C-shaped support structure as shown below in Figure 5-7:.

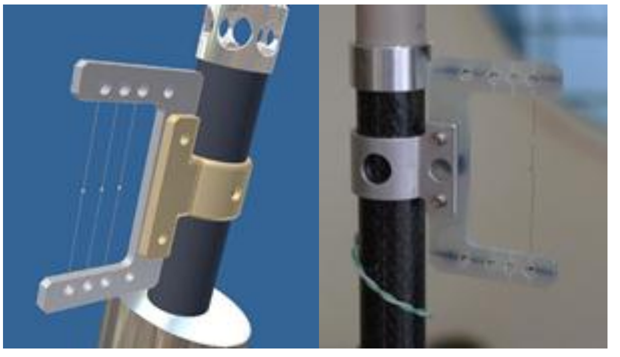


Figure 5-7: Temperature sensor mounted on the mast

In total there are four temperature sensors mounted on the mast.

5.4.6.3 Wind Sensor

The key instrument at the top of the mast is an ultrasonic wind sensor. This is a two-way time-of-flight (TOF) measurement of ultrasonic pulses between a pair of ultrasound transducers separated by 10 cm. The average of the two TOF measurements gives the speed of sound; the difference of the two TOF measurements gives the speed of the medium, i.e. the wind velocity component parallel to the axis of the transducer pair. A 3-D anemometer consists of transducer pairs arranged with mutually orthogonal axes in order to measure a full 3-D wind vector. A single time of flight measurement takes less than 1 ms, so in theory measurement rates of over 100 Hz are possible. In practice, once multiple time of flight measurements have been averaged for noise reduction, measurement rates of greater than 10 Hz are possible. This is more than sufficient to resolve individual eddies for eddy covariance flux measurements.

The final arrangement of transducers is yet to be optimised but would in all cases fit within a cylindrical volume, 15 cm in diameter x 15 cm in height, whose axis is aligned with the top section of the mast. The current best estimate for transducer layout suggests that a volume of 10 cm diameter x 10 cm height should be sufficient, but 50% margin has been added to this to allow for design immaturity.

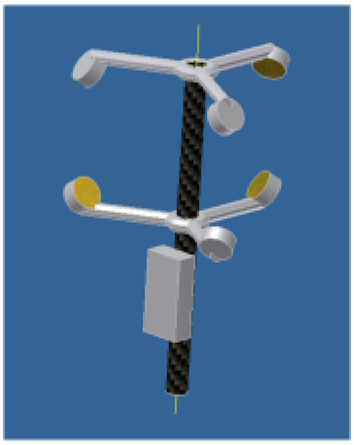


Figure 5-8: Possible arrangements for a sonic anemometer. Shown is a commercial sensor (Gill instruments). The volume proposed for MarsFAST model payload wind sensor head is 150 mm Ø x 150 mm H.

5.4.6.4 Tunable Laser Spectrometer (TLS)

The tunable laser spectrometer will detect trace concentration of water and volatiles. The laser light sources are tunable laser diodes; each laser diode is tuned to a spectral region which includes absorption lines of interest for the relevant gases. Several diodes can be used to allow optimum sensitivity to different gases, e.g. water and methane.

The TLS instrument is mast mounted. It is further assumed it can be placed on the top part of the 1st segment Eventually it requires a more detailed analysis that no severe disturbances are expected so close to the lander surface. The sensitive portion of the TLS is a multi-pass optical cell, that consists of two mirrors separated from each other by a distance of 20-30 cm. Because it is a multi-pass cell, the optical path achieved is much greater, typically of order of 10 metres, allowing sensitivity to the gases. A similar instrument has been flown on the ill fated Mars Polar Lander mission (215RD[6]).

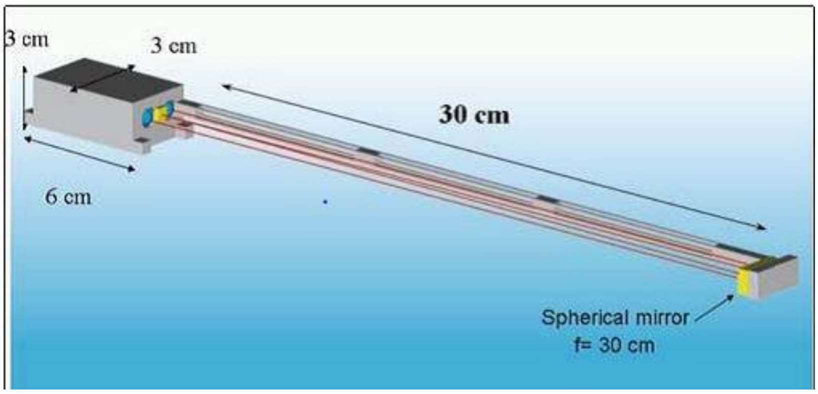


Figure 5-9: Conceptual design of a tunable laser spectrometer by RD[7]

5.4.6.5 Electric field sensor

The electric field sensor measures both the AC and DC components of vertical electric field. The DC component is important to measure in order to understand the global electric circuit, and may have important implications for atmospheric chemistry. The AC component is indicative of local triboelectric charging which may be associated with dusty turbulence, and carries information about more distant electrical phenomena.

The instrument proposed here is based on the ExoMars ARES instrument. The ARES instrument was mounted on the AEP boom in exactly the same manner is proposed in the present document.

The ARES instrument consists of two electrodes, each with a surface area of 100 cm^2, which are separated by a vertical distance of order 50 cm. Each electrode is 10 cm high and has an elliptical cross-section with a 10 cm circumference. The elliptical cross-section allows for more efficient packing of a hinged multi-segment boom. Coaxial cables join each electrode to the ARES electronics board which is located inside the atmospheric suite electronics compartment, inside the lander's warm enclosure.

5.4.6.6 Dust impact sensor

It is thought that the dominant dust-lifting process on Mars is called saltation. Large 'sand' particles, with diameters > 50 µm, are lifted more easily than small 'dust' particles (diameters < 10 µm) due to their larger surface area, but are too heavy to remain airborne for more than a few tens of seconds. When these sand particles fall back to the surface their kinetic energy releases smaller dust particles into the air.

This sensor measures the number and momentum of airborne sand particles, in order to quantify whether saltation is taking place and to correlate the amount of saltation with meteorological parameters such as wind speed or gustiness. By assuming that the speed of the sand particles is the same as the wind speed, estimates of the mass of the particles may be reached.

The sensor consists of two piezoelectric co-polymer films (material is P(VDF-TrFE)) bonded around the base of the mast (see picture below). Each covers 180 degrees of the circumference of the mast. The films themselves are of negligible mass; they are connected by coax cables to the proximity electronics box at the base of the mass.

The saltation sensor was part of the ExoMars AEP payload. In AEP it was called a 'dust sensor' but this name was misleading, as the sensor is not sensitive to small dust particles but rather to larger sand particles.

5.4.6.7 Humidity transducer

The humidity transducer is based on a HumiCAP capacitive transducer from Vaisala Inc. This transducer was developed for use in stratospheric sounding balloons, several thousand are used every day for this purpose on Earth.

The transducer consists of a capacitor, at the core of which is a polymer film which exchanges water vapour with the atmosphere. The capacitance changes according to the amount of water vapour it has adsorbed from the atmosphere. The nominal capacitance is a few picoFarads, with a dynamic range of ~1 pF.

The sensor head includes its own proximity electronics, capable of operating at ambient Martian temperature.

5.4.6.8 Pressure sensor

The baseline pressure transducer is a BaroCAP capacitive transducer from Vaisala inc.

The pressure transducer is housed within the warm lander enclosure, as part of the atmospheric central electronics.

The housing for the pressure transducer is likely to be similar to that used for MSL and Phoenix landers (pending further details of the lander interface). Note that it will be necessary to connect the pressure transducer to the atmosphere using a thin tube (1 mm I.D., TBC – design chosen to ensure minimal heat leak).

5.5 Payload Options

The proposed model payload serves the goal to study the feasibility of this MarsFAST mission concept and compliance with its objectives. Since the individual payloads are rather placeholder for instruments with similar resource, accommodation and operation requirements the actual selected suite of payload instruments may look different.

5.6 Payload Operations

The mission distinguishes two different main cases of science operations within the Nominal Operations phase as defined by Systems. The first is based on a standard procedure for daily science operations. This includes per sol:

- 1 panoramic image by the stereo camera
- 10 high resolution images
- Frequent meteorological observation

The meteorological package distinguishes two different operational sequences. In the sequence "high" the instruments are run in a high data acquisition mode to collect detailed high resolution data. The sequence "low" is used to collect frequent data to monitor at lower resolution the daily fluctuation of meteorological data. Table 5-3: summarises these operational phase and reflect on the data volume production and energy consumption.

OPERATIONS	**SteroCam**	**HiResCam**	**MeteoPack high**	**MeteoPack low**	**Σ**
Operation power ave. [W]	10	10	8	6	
Duration of 1 measurements [s]	120	120	1800	300	
Number of measurements per investigations	8 images (1 panorama)	10	1	1	
Duration of 1 investigation [s] (minutes)	960 (16')	1200 (20')	1800 (30')	300 (5')	
Day/night	day	day	day	day/night	
Repetition of investigation throughout nominal operations phase	1x every sol	1x every sol	2x very sol	2x every hour	

Wh per investigation	2.67	3.33	4.0	0.5	
Wh incl warming up (10%) per investigation	2.94	3.67	4.4	0.55	**11.82 Wh**
ROV-SSS (60min)	2.94	3.67	8.8	--	**15.41 Wh**
ROV TRA (240min)	--	--	--	4.4	**4.4 Wh**
Data vol. per measurement	2048x2048x16, 2 camera heads 134.23 Mbit	2048x2048x16 67 Mbit	See below		
Data vol. per investigation	1.08 Gbit (8 mast positions)	670 Mbit	8 Mbit		
Data vol. incl. HK	1.088 Gbit	678 Mbit	8.8 Mbit		
ROV-SSS Data vol incl. compression	72.534 Mbit (1/15)	45.20 (1/15)	2.2 (1/4)		**119.934 Mbit**

Table 5-3: Summarising the daily science operations including data volume production and energy consumption. ROV-SSS refers to the mission phases "Short Science Stop" and ROV TRA to the mission phase "traverse" when the rover is moving

It is interesting to note that the "low" sequence of the Meteorological Package may have severe impact on the energy budget. It is desirable to run the set of instruments twice per hour for 5 minutes. It appears practical for such frequent operations to leave the package in stand-by mode for quick stabilisation of the measurements. Under the assumptions of 2 W stand-by power the total energy consumed during one sol would accumulate to ~37 Wh. This is more than 3 times the energy needed for standard daily instrument operations. Also it seems not likely that such a high demand can be supported by the system design of the rover. A more detailed analysis on the actual operational requirements of the individual elements of this package is required at a later stage.

The second main case of science operations is dedicated to the in-situ investigation of Martian soil and rocks also planned to happen during the system Nominal Operations phase only . In this phase the sampling site will be approached, a sample taken and analysed. In total 20 of these dedicated stops are envisaged in the case of the MarsFAST mission timeline plan. Table 5-4: summarises the data volume and energy balance per instrument during this phase.

OPERATIONS	**Mössbauer**	**OSL**	**CloseUp Camera**	**ATR**	**Σ**
Operation power [W]	4	12 (peak 35)	8	3	
Duration of 1 measurements [s]	3600	1200	120	300	
Number of measurements per investigations	1	3	10	3	

OPERATIONS	Mössbauer	OSL	CloseUp Camera	ATR	Σ
Duration of one investigation [s] (minutes)	3600 (60')	3600 (60')	1200 (20')	900 (15')	
Day/night	night	day	day	day	
Repetition of investigation throughout mission	20	20	20	20	
Wh per investigation	4	12	2.66	0.75	
Wh incl warming up (10%) per sol	4.4	12.12	2.93	0.83	**20.28 Wh**
ROV-SSL (155min)	--	12.12	2.93	0.83	**15.88 Wh**
Data vol. per measurement	4 Mbit	4 Mbit	2048x2048x16 68 Mbit	22 (image + spectrum)	
Data vol. per investigation	4 Mbit	12 Mbit	680 Mbit	66 Mbit	
Data vol. incl HK	4.4 Mbit	13.2 Mbit	688 Mbit	72.6	
Data vol. incl compression	0.44 Mbit (1/10)	1.32 Mbit (1/10)	45.87 Mbit (1/15)	4.84 Mbit (1/15)	**52.47 Mbit**
ROV-SSL	--	1.32 Mbit	45.87 Mbit	4.84 (Mbit)	**52.03 Mbit**

Table 5-4: In-situ investigations during a science stop by the rover. ROV-SSL refers to the mission phase "Science Stop Long", the Mössbauer spectrometer is baselined to be operated only during night-time.

6 LANDING PLATFORM

The information contained in this chapter has been provided by the JPL team of experts who have supported the study for the platform aspects.

6.1 Overview

The landing platform is designed to land a ~150 kg rover and an additional ~50 kg of egress hardware using the Mars Science Laboratory (MSL) Entry, Descent, and Landing (EDL) system with a launch in 2024 or later (up to 2034). The platform is based on the landing platform originally conceived for the Mars Astrobiology Explorer - Cacher (MAX-C) and ExoMars rovers in the 2011 timeframe.

The landing range for the joint mission includes latitudes between 20N and 5S. The platform is designed to control EDL (in place of a NASA rover) and support a TBD science payload (discussed briefly below) for 0.5 – 1 Martian year. The platform would be solar powered, and telecom would rely on Mars orbiter relay (UHF) with a Direct-To-Earth backup capability. For planning purposes, NASA assumed an Atlas V launch vehicle. The mission duration would be approximately 8 months in cruise, and 1 Martian year on the surface for the platform itself.

6.2 Launch, Cruise, and Entry, Descent, and Landing

Launch, Cruise, and EDL phases of the mission are expected to be similar to that of MSL.

The launch/injection phase includes terminal countdown, launch, and final stage separation. The proposed mission concept would launch from the KSC Cape Canaveral Air Force Station Eastern Test Range (CCAFS/ETR). The launch vehicle would be expected to be in the Atlas-V family-class of launch vehicle performance capability. Payload would be in a power-off state during the launch/injection phase.

The cruise phase would begin when the spacecraft separates from the launch vehicle and end prior to entry, descent, and landing (EDL). The ESA rover and platform would be enclosed inside an aeroshell during cruise.

Routine spacecraft health checks would be performed during cruise, and the ESA rover would be able to perform checks as needed. There are possible thermal issues that may arise during checks, and these are discussed in the thermal section below.

The cruise stage itself would not have a dedicated flight computer or relay capability, and it would utilise the platform's flight computer and relay capability. During checks in cruise, the ESA rover would be powered by and receive and transmit data through interfaces with the platform. Otherwise, it is assumed that the rover would be in a powered-off state with thermal requirements maintained by the cruise/platform system.

The platform EDL system would be based heavily on the as-flown 2011 MSL EDL architecture. In order to meet the requirements of the platform and of the rover egress system, the EDL system would employ hazard detection and avoidance (HDA) and terrain relative navigation (TRN) for a step height requirement off the platform of 0.2-0.4 m (which may include rocks up to 0.2 m in height) and to meet a platform angle requirement of between ±30°. At this time, the technology to identify a rock at 0.2 m would need to be developed.

After landing, the platform would stabilise itself in a TBD sequence that would last approximately one hour (estimate). At that point, the platform and ESA rover would be able to deploy their solar arrays in sequence such that neither system interferes with the other; initial commands for ESA rover deployments would be able to be received/transmitted through the platform telecom system. The platform would deploy its mast with stereo camera during this time, and imagery from this camera would be available to the ESA rover team to plan egress. The ESA rover would be responsible for controlling and powering the deployment of their egress hardware and any other hardware (mast, etc.) needed for egress.

6.3 Mechanical and Configuration

The platform landing system was designed to deliver approximately 800 kg total (platform, science payload, rover, and egress; a conservative estimate) to the Martian surface. Initial studies resulted in a landed system of approximately 700 kg, including rover and egress. This included 150 kg for the rover, 50 kg for egress, 52 kg for science payload on the platform, 366 kg for the platform and its subsystems, and the remainder for contingency (15% for science payload, 24% for the platform itself). The Descent Stage and Cruise Stage were assumed to be build-to-print from MSL.

Interfaces to the ESA rover and egress hardware were assumed to be static non-isolated inserts, with all kinematic, thermal, and electrical isolation managed on the rover side.

The platform itself (see figures) would consist of a roughly hexagonal pallet with a honeycomb top deck and a six-outrigger support structure. The landing mechanism would consist of six deployable hinged panels consisting of honeycomb crushable material with six edge-protection airbags that would deploy behind the crushable panels during final descent. These airbags would be retracted after landing to allow the egress hardware to be deployed. The platform has cut-out areas to accommodate the descent stage hardware, and these cut-outs have been increased in size near the rover to accommodate better the rover egress hardware. Depending on potential NASA science payloads, additional adjustments in the platform (including possible cut-outs) may need to be made.

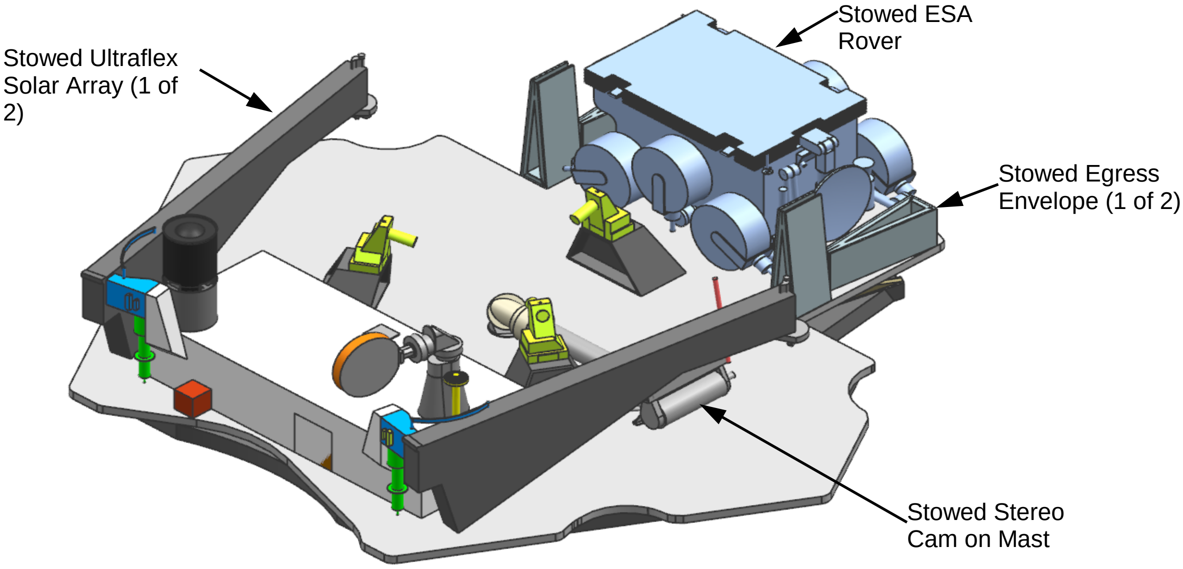


Figure 6-1: Landing Platform – Stowed Configuration

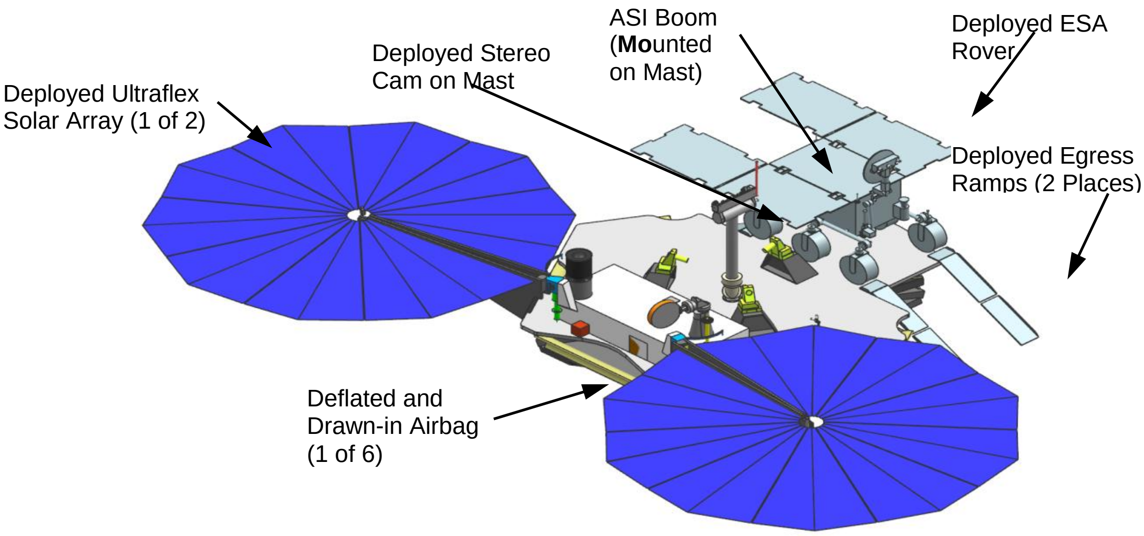


Figure 6-2: Landing Platform – Deployed Configuration

6.4 Power

The platform would use two 3.5 m Ultraflex solar arrays to power its subsystems and science payload. The arrays were sized to support a Martian-year-long platform science mission based on dust and temperature environments used to design the Insight mission. The arrays on this mission would be significantly larger than those on Insight (2.18m diameter) as a result of potential landing latitudes and mission duration. Drivers for this mission would include survival in sleep mode during a global dust storm at 20N and operating in a low-power science mode through the winter at 5S. No solar array dust cleaning technology has been assumed to be employed, and the arrays are not currently designed with gimbals.

The power avionics would be based on those from MSL. The preliminary mission/science payload can be supported with one 74Ah battery. Telecom uplinks would be assumed to occur during the day.

During cruise, the cruise stage solar arrays would be used to supply power to the ESA rover. At 24 hours prior to EDL, the ESA rover would be required to survive on its own power (with no additional power from the cruise/EDL/platform system) until the rover could deploy its solar arrays no earlier than one hour post landing. It is assumed that there would be enough time post landing and prior to sunset for both the platform and the rover to power their respective batteries for surviving the first night.

6.5 Avionics

All avionics for this mission would be inherited from MSL and would be build-to-print except for obsolete parts. The avionics on the platform would control all cruise and EDL functions in addition to all functions during the surface mission.

6.6 Thermal

The lander thermal control system would leverage MER and MSL heritage with previous studies done for the MAX-C/ExoMars concept. Survival heating power requirements during winter (depending on latitude and payload requirements) may drive the design to use RHUs, and future studies would address this issue.

During cruise, ESA has requested two rover check-outs, dissipating 100 W for about two hours during each event. The baseline design would require ESA to accommodate the requested operations with their rover's own thermal control design, decreasing dissipation, or by other necessary means. The other option would require the rover to tie into the cruise stage or platform Heat Rejection System (HRS). This would increase landed mass, design complexity, controlled interfaces, and cost. The current thermal control design would maintain independence between NASA and ESA components.

6.7 Science Payload

A number of potential science payloads that would utilise a stationary platform were developed for this study. None of these payloads included life detection experiments. The payload concepts are as follows:

1. Atmosphere/weather, soil moisture, subsurface, tectonics
2. Payload 1 + dust, pollution, composition
3. Payload 2 + elemental composition, atmospheric composition
4. "Deep drill" and geologic characterization

For this particular study, Payload 1 was incorporated. The instruments in this payload included (among others) a stereo camera, meteorological package, seismometer, and ground penetrating radar. With contingency, the mass of this payload would be approximately 52 kg.

To survive low power periods (winter or dust storm), several payload operational modes were developed where instruments were operated on low duty cycles (or placed in survival mode if appropriate) in order to maintain the long-term meteorological and seismic records.

7 SYSTEMS

7.1 System Requirements and Design Drivers

7.1.1 System Requirements

The following requirements have been used for the design of the CDF MarsFAST concept and were refined based on the study outcomes where applicable.

General Requirements	
Req. ID	**STATEMENT**
GE-010	The MarsFAST rover shall allow demonstration of the MSR FAST mobility performance requirements: capable to traverse at least 15 km straight line (goal of 20 km) on a mission operations timeline of a maximum of 110 sols without the support of radioisotopic material for power generation or thermal control. *Comment: A factor of path "bending" shall be taken into account to derive the expected total accumulated ground track by considering the MarsFAST locomotion s/s terrain negotiation capabilities (e.g. was 30%).*
GE-020	The rover shall accommodate, carry and operate a reference science payload.
GE-030	The reference science payload of the rover shall allow remote sensing & in-situ science & sampling handling and analysis.
GE-040	The rover mass should not exceed 150 kg including system margins and appropriate maturity margins. *Comment: This value is set as reference value for the study approach. The critical requirement is that the total ESA elements (rover & egress system) shall not exceed 200kg including system margins (See requirement IF-010 for more details).*
GE-050	The total allocated mass of HDRM & interface with the Sky-crane and/or platform should not exceed 50 kg including system margins and appropriate maturity margins. *Comment: This value is set as reference value for the study approach. The critical requirement is that the total ESA elements (rover & egress system) shall not exceed 200kg including system margins(See requirement IF-010 for more details).*
GE-060	The maximum volume allowable for the rover in stowed configuration (including the egress system) shall be less than 1.48m × 0.95m × 0.55m (LxWxH or WxLxH). *C: Some intrusion above the 0.55 m height could in further phases be negotiated with NASA for specific item(s).*
GE-070	The maximum volume allowable for the rover in deployed and ready-to-go (including deployed egress system) the configuration shall be less than TBD m × TBD m × TBD m. *C: Maximum allowable volume shall not protrude into the centre of the pallet direction. Vertical, right and left side directions are in principle possible to*

<table>
<tr><td></td><td>expand (TBC during the study with JPL interface).</td></tr>
<tr><td>GE-080</td><td>The rover surface mission shall consider as a reference scenario an arrival date Ls 133 (Sep 2025) according to the launch date 2024.
C: The sensitivity of this operational scenario with respect to the other launch dates from 2024 to 2034 shall also be assessed during the study.</td></tr>
<tr><td>GE-090</td><td>The rover shall operate at a latitude between 5deg South and 20deg North.</td></tr>
<tr><td>GE-100</td><td>The rover shall operate at an altitude range of -2000m to +1000m MOLA (compatibility with the EDL Sky-crane system).</td></tr>
<tr><td>GE-110</td><td>The rover lifetime on the Mars surface shall be a minimum of 180 sols.
C: This lifetime accounts for the nominal surface lifetime, which starts at landing and shall include all the rover early operations (i.e. post landing checkouts, egress, preparation to departure, etc.), contingencies (i.e. solar conjunctions, local dust storms).</td></tr>
<tr><td>GE-120</td><td>The rover shall conform to Category IVa Planetary Protection requirements: Mars surface mission with no life detection and no special regions.
C: Planetary Protection requirements may be more stringent for an MSR fetching rover. This relaxation is deemed acceptable for demonstration purpose.</td></tr>
<tr><td>GE-125</td><td>The rover shall be capable of completing the reference mission scenario with the following environmental design guidelines:
<u>OPTICAL DEPTH</u>
<table>
<tr><th>Ls (deg)</th><th>Recommended design Optical Depth for SFR</th></tr>
<tr><td>0-40</td><td>1 constant</td></tr>
<tr><td>40-180</td><td>0.5 constant</td></tr>
<tr><td>180-192</td><td>1 constant</td></tr>
<tr><td>192-220</td><td>1 constant</td></tr>
<tr><td>220-260</td><td>1.5 constant</td></tr>
<tr><td>260-310</td><td>>4</td></tr>
<tr><td>310-340</td><td>1 constant</td></tr>
<tr><td>340-360</td><td>1 constant</td></tr>
<tr><td>N/A</td><td>2 constant</td></tr>
</table>
Basically, the distinction between global and local dust storms can be schematically explained as follow:
• Global dust storms:</td></tr>
</table>

<table>
<tr><td></td><td>

Maximum two per year and may vary from 35 to 70 days or more. Although global dust storms do not occur every year, their occurrence is fairly frequent.
Global dust storms begin when insolation is maximum.
Have an optical depth typically between 2 and 5 but might rise to 10.

Local dust storms:

They occur at almost all latitudes and throughout the year, and may occur several times within a surface mission time. However, they have been observed to occur more frequently in the approximate latitude belt 10°N-20°N and 20°S-40°S with more dust clouds seen in the south than in the north, the majority occurred during the southern spring.
Based on the orbiters observations, it is estimated that more than 100 local storms occur in a given Martian year (783 observed in 1999 by MGS).
They last a few days (15 sols maximum).
These gusts, or high turbulences periods have an optical depth typically between 0.5 and 2.
Requirement: For design purposes the surface element shall survive at least for the occurrence of a local dust storm with OD=2 with a duration of 14 sols at any moment of the mission lifetime.

<u>DUST DEPOSITION</u>
Following recommendations to be followed:
No natural dust removal by the wind shall be assumed in the design, however it has been observed in some previous surface missions
In order to avoid sand deposition on the photovoltaic cells, the solar panels shall be higher than 20cm from the ground
The degradation of solar array performance per sol due to dust deposition shall be modelled by applying the “Pathfinder Model”: (0.0018)x(Tau/Tau_average) being Tau=OD profile and Tau_average =0.5
</td></tr>
<tr><td>GE-130</td><td>The rover shall be capable of completing the reference mission in a Landing site environment defined by: 30 cm (TBC) rocks height and distribution, TDB soil properties, TBD maximum slope</td></tr>
<tr><td>GE-140</td><td>The rover shall maximise the science return (as a minimum TBC Mbits/sol) by considering three communications architectures
1) UHF only: reference orbiter : ExoMars TGO 2016 (circular orbit)
2) Relay orbiter in UHF and direct-to-Earth for basic/ contingency telemetry: Reference Orbit MarsExpress (Elliptical orbit)
3) Direct-to-Earth only
C: The study should check for each architecture the maximum capabilities that the rover can provide to comply with this requirement depending of the different</td></tr>
</table>

	mission phases and operational needs.
GE-150	The rover shall be designed with equipment compatible with TRL 5 by 2018. *C: Any deviation for this requirement can be discussed if deemed necessary.*

The ESA MarsFAST rover is transported to Mars on a pallet provided by NASA/JPL, which is lowered onto the surface via the Sky-crane Entry Descent and Landing system.

A large fraction of the pallet is reserved for other NASA/JPL element(s) and will not be part of this CDF study but some reference is provided in Chapter 6.

The following high level interface requirements and assumptions have been used for this CDF Study:

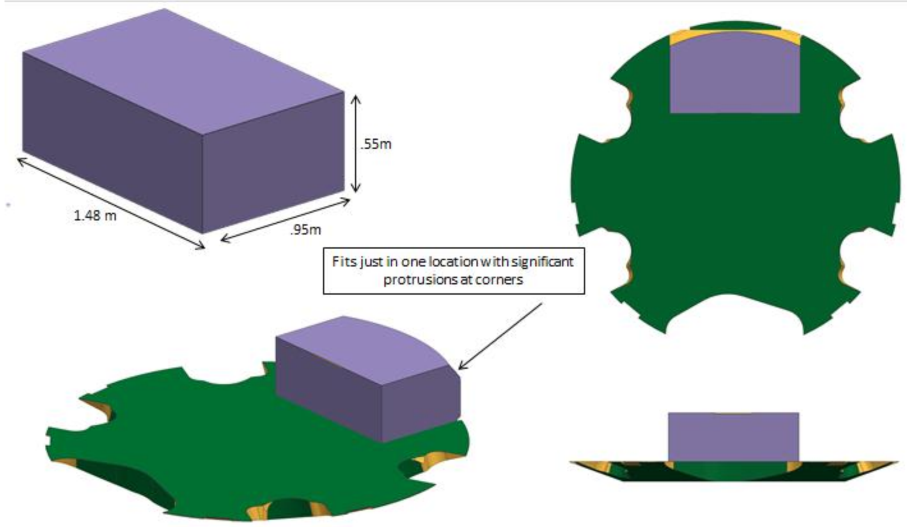
ESA/JPL Interfaces	
IF-010	Total ESA allowable mass for the given volume, see figure below, shall not exceed 200 kg including rover + egress system.  Figure : NASA/JPL provided envelope at the start of the study. (Credit to JPL) *Comment: This mass allocation is to be taken as the starting point considering packing efficiency from previous missions i.e. the final mass could be renegotiated as far as the specified volume is respected.*

Table 7-1: System requirements

Other assumptions to be considered for the rover design:

- Step Height of 0.2 to 0.4m (assuming Skycrane implemented with Hazard Detection and Avoidance system)
    - Vertical height from edge of pallet to ground
    - Part of this can be a rock up to 0.2m tall
    - Platform Angle between +/-30 Degrees Angle of platform relative to gravity vector can be anywhere between these values

  - Included in this envelope is contribution of the local slope of terrain, which may be +/- 20 Degrees
- Local terrain may consist of rocks up to .6m which may be located underneath or immediately adjacent to the platform
- NASA/JPL shall stabilise the pallet after landing.

7.1.2 Design Drivers

The following design drivers were identified:

- Fast and long distance mobility. This calls for the use of SPARTAN navigation technology (with fast image processing) currently developed at ESA and a robust locomotion subsystem design. Moreover this has an impact on daily energy required for locomotion
- Heating power required, especially in absence of RHUs
- Limited mass and volume available on pallet
- Implications of Direct-to-Earth (DTE) capabilities on accommodation (antenna) and energy budget
- Hibernation during local dust storms (optical depth of 2), lasting up to 14 sols

7.2 System Trade-Offs

No standard system level trade-offs have been performed. However the accommodation and configuration aspects of a number of items required some optimisation between subsystems, in particular Mechanisms (egress aids) and Robotics (locomotion); comms (high gain antenna), Science (pancam) and Navigation (GNC sensors) on the mast, and in general the trades for searching for innovated technologies which provide a compromise between readiness and miniaturisation/integration (ESA SPARTAN, ESA Dual UHF-X band transponders, ESA low temperature batteries, etc..).

However at system level, the main challenge has been to optimise the energy budget: tuning of durations of the system modes and reference sols was performed in order to make the mission concept compatible with the requested mission objectives: MSR mobility demonstration and maximise the science return of the concept..

7.3 Mission Architecture

The key characteristics of the MarsFAST mission are provided in Table 2-1.

MarsFAST Mission Characteristics		
Programmatics	Launch date	October 2024
	Arrival date	September 2025
	TRL	At least TRL 6 (new ISO scale) at start of phase B2
	Model philosophy	STM + Locomotion BB + ATB + EQM + PFM + Spares
	Design lifetime	180 sols on Martian surface

	Planetary Protection	Category IVa requirements apply
Launch Segment	Launcher	Atlas V
	Launch site	KSC Cape Canaveral Air Force Station Eastern Test Range (CCAFS/ETR)
Space Segment	Cruise stage	Provided by NASA/JPL
	Landing platform	Mars Science Laboratory (MSL) Entry, Descent, and Landing (EDL) system (Sky Crane concept) provided by NASA/JPL
	Data relay orbiter	TBD
	Mars rover	MarsFAST rover (see Table 2-2)
	Egress system	MarsFAST egress system (see Table 2-2)
Ground Segment	Ground stations	Three ESA 35 m Deep Space Antennas (New Norcia, Malargüe, Cebreros) for DTE during surface operations No ESA ground station coverage before surface operations
	Mission operations	MOC at ESOC
	Science operations	Early surface operations phases: MOC and SOC integrated at ESOC For later phases: remote access for the mission scientists

Table 7-2: MarsFAST mission characteristics

ESA is providing the rover and its egress system which is the subject of this report. Both are to be accommodated on the NASA pallet. The powering and commanding of the egress system is done by ESA via the rover. Figure 7-1 shows the elements of the mission architecture that have been analysed during this CDF study.

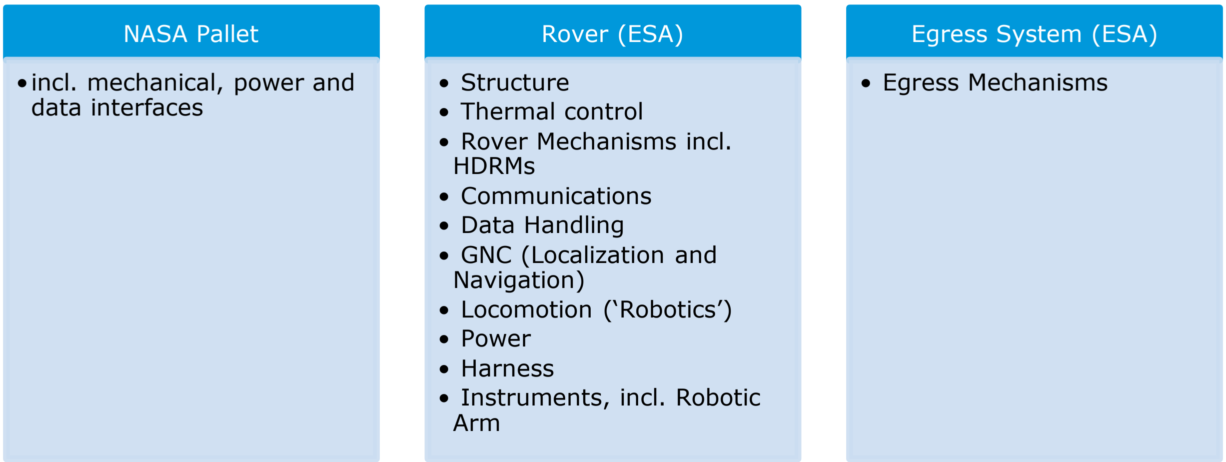


Figure 7-1: Reference MarsFAST Mission Architecture

7.3.1 Mission Phases

The following six mission phases have been defined for the MarsFAST mission concept:

1. Launch and Cruise Phase
2. Entry, Descent and Landing Phase
3. Deployment Phase
4. Egress Phase
5. Commissioning and Early Operations Phase
6. Rover Operations Phase (Science and fast transversing operations)

Based on the above phases, the rover system modes, reference sols, as well as the mission timeline have been defined and are presented hereafter.

7.3.2 Rover Modes

Throughout the MarsFAST CDF study, several system modes have been identified for the rover. Among these, the focus was put on those system modes that were found to be sizing w.r.t. the design of the thermal and / or power subsystem. These ten sizing modes are depicted in Figure 7-2.

Additional non-sizing rover modes are listed in Figure 7-3.

Number	Mode Name	Definition
1	EDL Mode	***From 24 hours before EDL to first morning after landing*** Rover powered by batteries only First TM set to be sent by NASA platform (Comms on Rover OFF) Heaters ON during first night All other EQT is OFF Critical deployments between 4pm and 6pm: egress system and solar panels as much as possible
2	Deployment Mode	***First morning after landing*** Non-critical deployment and rover checkout for all S/Ss required for egress Rover is powered by fully deployed solar array
3	Traverse Mode	***Traversing with science and communication*** Locomotion and navigation ON Meteopack low is OFF Only during daytime Rx ON (UHF)
4	Science Stop Short Mode	***Frequent scientific measurements*** Stereo or HighRes Cam ON Meteopack high and low ON No driving Rx ON (UHF) Batteries are being charged During daytime
5	Science Stop Long Mode	***Daytime science*** Meteopack low ON Daytime science (ATR, OSL, Close-up Cam, sampling) ON Rx ON (UHF) Duration: full sol during daytime Batteries are being charged No driving
6	Science Stop Night Mode	***Nighttime science*** Rover powered by batteries only Mössbauer operated during nighttime for 60 mins. Meteo pack low ON
7	Nominal Night Mode	***Nighttime idle*** Rover powered by batteries only All EQT in power saving state as far as possible Meteo pack low OFF Housekeeping EQT ON Heaters ON OBC STDB UHF EQT ON for 7 min per night
8	DTE Communications Mode	***Pre-planned communications session*** No driving DTE comms EQT ON No science except meteopack low During daytime
9	Idle Mode Day	***Daytime idle*** Rover powered by solar arrays, batteries being charged All EQT in power saving state as far as possible Meteo pack low ON Housekeeping EQT ON OBC STDB UHF EQT ON for 14 min per day
10	Hibernation Mode	***Ensuring survival in case of local dust storms (0.5 ≤ OD ≤ 2)*** All EQT and OBC OFF, timer ON PCDU heaters line ON Heaters ON Comms OFF During day- and nighttime

Figure 7-2: Sizing rover modes

Launch/Off Mode	***During launch and in case of power subsystem anomaly*** All EQT OFF Health test checks during travel to Mars foreseen
Safe Mode Day	***Entered in case of contingencies*** Low power survival mode UHF Receiver ON during small fraction of time (Comms in listening mode) OBC OFF vs. switched ON at hail reception Science data to be stored without loss of information During daytime
Safe Mode Night	***Entered in case of contingencies*** Low power survival mode UHF Receiver ON during small fraction of time (Comms in listening mode) OBC OFF vs. switched ON at hail reception Heaters ON Science data to be stored without loss of information During nighttime

Figure 7-3: Additional non-sizing rover modes

7.3.3 Reference Sols

Representative sol types can be defined as scenarios for verification of appropriate sizing. During the MarsFAST CDF study, a set of reference sols has been defined based on the following assumptions:

- The term “sol” is used to denote a complete diurnal cycle of Mars
  - Earth time per sol: 24 hrs 40 min
  - Daylight per sol: 11 Earth hrs for traversing demonstration phase, 10 Earth hrs for science operations phase
- At least two communication slots per sol are foreseen
  - Uplink of sol plan either early in the morning (DTE (30mins) or UHF (7mins)) or during the night (Only UHF(7mins))
  - Downlink of high priority data required for planning of the next sol either in the afternoon (DTE (5mins)) or during the night (only UHF (7mins))
- Rover operations can only start when enough power is available for the mode and the environmental temperature allows the required equipment to be within the operating temperature limits, specially for those not pre-heated.
- The surface operations shall be shared to fulfil mobility capability assessment as well as acquisition of scientific data
  - Science acquisition is assumed to require “daily” involvement of ground control (science plus engineering planning), assisted by on-ground planning tools and a degree of on-board autonomy
  - Mobility capability assessment can eventually run fairly autonomous, but should be performed in a stepwise manner, i.e. “daily” interaction of ground control in early mission phases.

For the purpose of the energy budget sizing exercise, the objective was to compose the reference sols of the pre-defined rover modes which are considered potentially sizing w.r.t. the TCS or Power subsystem design. Amongst all identified rover modes, the

Traverse Sol, the Contact Science Sol and the Hibernation Sol were found to be the most demanding with respect to the sizing of the power subsystem.

Traverse Sol

Mode	Description	Duration [min]	Day/Night
Idle day	2 hrs pre-heating + 7 min UHF Communication + rest of daytime	375	Day
DTE Communications	5 min download DTE, 0.5 hrs upload DFE	35	
Traverse	4 hrs	240	
Science Stop Short	10 min	10	
Nominal Night	entire night duration incl. 7 min UHF Communication	820	Night

Figure 7-4: Traverse Sol definition

During the Traverse Sol the rover enters four different system modes during the day and remains in the Nominal Night Mode, i.e. without doing any science operations, during the night. The 11 hours of daytime mainly consist of two hours for pre-heating of the rover equipment in the morning and 4 hours for traversing. The latter is needed to achieve the required minimum distance for the fast moving demonstration. Due to power reasons, the duration allocated for DTE and DFE communications as well as for the Science Stop Short mode has been reduced drastically for the given worst case scenario (latitude, temperature environment, etc.). The remaining time of the sol, the rover spends in the Idle Day Mode. An overview of the Traverse Sol is provided in Figure 7-4. In more favourable conditions (e.g. different latitude), the scenario can be re-defined, allowing e.g. more traverse time or additional DTE communication.

Contact Science Sol (with night time science and DTE uplink)

Mode	Duration	Duration [min]	Day/Night
Idle day	2 hrs pre-heating + 7 min UHF Communication + rest of daytime	355	Day
DTE Communications	DTE uplink 0.5 hr	30	
Science Stop Long	1/2 h coring, 1/2 h Rob arm operation, 95 min instruments operations	155	
Science Stop Short	2 x 30 min	60	
Science Stop Night	1 hr	60	Night
Nominal Night	entire night duration incl. 7 min UHF Communication	820	

Figure 7-5: Contact Science Sol definition

The purpose of the Contact Science Sol is to gather as much scientific data as possible. Therefore, after 2 hours of pre-heating, the rover carries out scientific measurements during day- and night time. Communications during this sol type is foreseen to be via DTE uplink for 30 min and via UHF up- and downlink for each 7 min during day and night. The remaining time of the sol, the rover spends in the Idle Day and Nominal Night mode respectively. The overview of the Contact Science Sol is provided in Figure 7-5.

Hibernation Sol

Mode	Description	Duration [min]	Day/Night
Hibernation	entire daytime	660	Day
Hibernation	entire nighttime	820	Night

Figure 7-6: Hibernation Sol definition

The rover is foreseen to enter the Hibernation mode to ensure survival in case of local dust storms. The Hibernation Sol reflects an entire sol during which the rover remains in Hibernation mode.

Besides the above, further reference sols have been identified for deployment, egress, commissioning, contact science preparation, and survival during contingencies.

7.3.4 Mission Timeline

Figure 7-7 depicts the mission timeline for the MarsFAST mission. It is shown that within the minimum rover lifetime of 180 sols, the verification of the required MSR fast mobility capability as well as the foreseen scientific measurements can be achieved.

Phase	Duration	Unit	Description
Launch	approx. 1	day	Launch Date: 2024 (baseline), 2026 (back-up)
Cruise	11	months	Launch Oct. 2024, arrival Sep. 2025
	10	months	Launch Nov. 2026, arrival Sep. 2027
Entry Descent and Landing	1.6	sols	From 1 sol prior to EDL until the first morning (6am local solar time) Critical deployments between 4pm and 6pm: egress system and solar panels as much as possible
Deployment	8	sols	Non-critical deployment and rover checkout for all S/Ss required for egress
Egress	4	sols	Uplink via DFE and downlink via UHF
Commissioning and Early Operations	10	sols	Complete testing of functionalities related to mobility Instrument calibration Initial traversing with continuously increasing travel distance
Nominal Operations	95	sols	Total: 180 sols rover lifetime on Mars
	55	sols	Traversing (10 sols demonstration of fast traversing)
	20	sols	Contact Science Sol Type 4 with Nighttime Science and DFE uplink
	20	sols	Contact Science Preparation Sol
Contingencies	63	sols	
	30	sols	Conjunction Allocation (1x per scenario)
	14	sols	Allocation for local dust storms (OD = 2)
	19	sols	20% margin for operational contingency during nominal operations
Potential mission extension	TBD	sols	
Total available sols	**180**	**sols**	GE-110: The rover lifetime on the Mars surface shall be a minimum of 180 sols
Total allocated sols	**180**	**sols**	Allocation for Deployment, Egress, Commissioning and Early Operations, and Nominal Operations Phase as well as Contingencies
Delta w.r.t. total available sols	**0**	**sols**	

Figure 7-7: MarsFAST reference mission timeline

The sequence of reference sols is depicted in Figure 7-8. For the sequential planning of sols throughout the mission lifetime, the 30 sol solar conjunction – starting at sol 110 in the case of the MarsFAST mission reference scenario (i.e. arrival in Sep 2025, Ls133)– needs to be taken into account. Since in this reference mission scenario the fast roving capability demonstration has to be finished before the start of the solar conjunction and flawless traversing has to be practiced in advance, the 10 sol fast roving demonstration starts at sol 101.

During this demonstration the rover speed of 1.8 cm/s is representative of the required speed of the fast roving capability. Demonstrating this capability over 10 sols after a previous mission duration of 100 sols, provides a representative validation under the given environmnental conditions, such as solar cell efficiency degradation, wear of the wheels and mechanisms and battery performance.

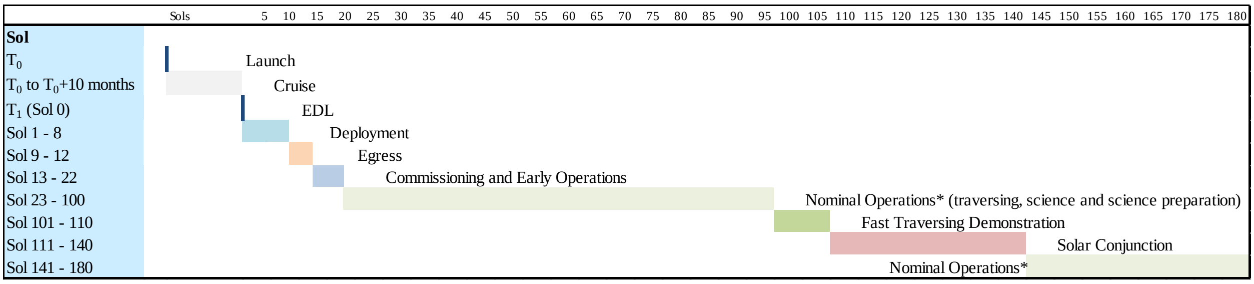


Figure 7-8: Sequence of reference sols throughout mission lifetime for the MarsFAST reference scenario (i.e. arrival in Sep 2025, Ls 133)

* Note: Local dust storms could occur at any time during the MarsFAST surface lifetime. This reference timeline assumes a contingency allocation of 14 sols (i.e. MarsFAST hibernation mode) at any time during Nominal Operations. Should a local dust storm happen at any other surface mission phase (e.g. Deployment, Egress, Commissioning and Early Operations), the mission timeline can be adjusted accordingly.

Besides the allocation for local dust storms, a 20% margin (19 sols) for operational contingencies is also included within the total of 118 sols Nominal Operations.

The timeline depicted in Figure 7-7 applies to the reference of arriving at Ls 133 (September 2025). As can be seen from Figure 4-1, the environmental conditions are sensitive to the arrival date. The opportunity two years later will move the arrival closer to the global dust storm season, which would also have impacts on the mission planning. The time for science operations would potentially be decreased in order to allow a fast traversing demonstration earlier in the mission. The following three opportunities will then have the arrival date in the global duststorm season, so the start of the nominal mission might have to be further postponed to wait for the end of the season. In any case the nominal mission time of 180 days cannot be guaranteed without dedicated duststorm survivability.

7.4 System Baseline Design

The baseline design presented in the following sections is based on the split into two modules under ESA responsibility: the rover and the egress system. It is envisaged to achieve a maximum independence from the landing platform provided by NASA/JPL and keep the interfaces to the pallet as simple as possible.

The egress system is designed to ensure safe (considering the terrain constraints resulting from the pallet landing capabilities) and smooth egress from the pallet after which the rover shall demonstrate its fast roving capability and conduct scientific measurements throughout its journey on Mars.

7.4.1 Overview

MarsFAST Rover Characteristics		
Mass	Payload	15.3 kg science payload
	Total	156.1 kg incl. 20 % system margin

Dimensions	Stowed	1159 mm x 530 mm x 910 mm
	Deployed	2309 mm x 1244 mm x 1815 mm
Structure	Composite sandwich moulding with CFRP faceskins and glass fibre reinforced plastic (GFRP) honeycomb core	
Mechanisms	HDRMs as required to fix appendixes (locomotion subsystem, mast for camera head and HGA, solar array and robotic arm) and body to the rover platform	
	Camera head and high gain antenna (HGA) are mounted – facing opposite directions – on a pan and tilt mechanism at the top of a short deployable mast	
	Actively controlled Solar Array Deployment Mechanisms	
	Corer / Grinder for the Attenuated Total Reflection spectrometer on the tip of the robotic arm	
Robotics	Locomotion Subsystem 6x6x6	6 rigid wheels: 30 cm diameter, 13 cm width
		2 side bogies plus 1 rear bogie 3 passive joints for stabilisation when traversing 3 motorised joints per wheel for deployment, driving and steering
		36 motion controllers in the warm box
	Robotic Arm	4DoF, 450 mm reachable sampling radius and compact stowed configuration achieved through 2 limbs and 4 joints
GNC	2 Navigation Cameras on the camera head on top of short mast at 1.1 m	
	2 Localisation Cameras on the front rover body	
	2 IMUs	
	1 Sun Sensor	
	1 Hazard Camera on the rear rover body	
	Limited autonomous navigation capability (SPARTAN) on dedicated FPGA (see Data Handling equipment)	
Power	Solar Array	2 deployable wings (2 panels each) and 1 body mounted solar panel Total solar panel area: 2.24 m^2 Solar cells: 3G30 (baseline) No dust removal system Average energy: 607Wh/m^2 per Sol
	Battery	7s12p, Li-ion cells: 18650 NL 653Wh EOL

		4.8 kg
	PCU	Unregulated bus architecture, MPPT
Communications	2 Dual UHF/X-Band Transponder	
	2 Travelling Wave Tube Amplifiers, 65 W RF output power	
	2 UHF low gain antenna, λ/4 monopole	
	1 metasurface X-band high gain antenna, 35 cm diameter	
	1 Radio Frequency Distribution Unit	
Data Handling	Single centralised unit implementing all C&DH functionality - hot redundant power conversion module, on-board timer, safeguard memory, reconfiguration module and telecommand decoder - cold redundant processor module, IO modules, mass memory modules and telemetry encoders - non redundant navigation processing HW, consisting of a co-processor and a dedicated ASIC/FPGA	
Thermal	Insulation on internal rover bathtub walls and around battery: 3 cm Aerogel (baseline), gas gap (option) Heaters to maintain the units within the allowable temperatures Remove of excess heat during operations using loop heat pipes and radiators	
Instruments	Panoramic Stereoscopic Camera and 1 High Resolution Camera mounted on a Mast	
	Close-up Imager mounted on Robotic Arm	
	Optically Stimulated Luminescence Dating Instrument	
	Mössbauer and X-Ray Fluorescence Spectrometer	
	Attenuated Total Reflection Spectroscope	
	Meteorological Package on Deployable Boom	
	MarsFAST Egress System Characteristics	
Egress System Mass	Dry mass	18.23 kg
	Total	21.87 kg incl. 20% system margin
Mechanisms	Egress ramps, spring actuated hinges and HDRMs	

Table 7-3: MarsFAST Rover and Egress System Main Characteristics

7.4.2 Mass Budget

The mass budget for the rover and egress system is provided in Table 7-4 and Table 7-5 respectively. A detailed breakdown of the contents per subsystem is provided in the equipment lists in Table 7-7 and Table 7-8.

Rover						
		Target Spacecraft Mass at Launch			150.00	kg
		ABOVE MASS TARGET BY:			-6.13	kg
	Without Margin	Margin		Total	% of Total	
Dry mass contributions		%	kg	kg		
Structure	8.42 kg	20.00	1.68	10.10	7.76	
Thermal Control	3.48 kg	10.72	0.37	3.85	2.96	
Mechanisms	7.93 kg	14.16	1.12	9.05	6.95	
Communications	12.20 kg	11.23	1.37	13.57	10.43	
Data Handling	5.50 kg	10.00	0.55	6.05	4.65	
GNC	1.80 kg	14.44	0.26	2.06	1.58	
Robotics	25.87 kg	18.66	4.83	30.70	23.60	
Power	27.70 kg	20.00	5.54	33.24	25.55	
Harness	6.20 kg	0.00	0.00	6.20	4.76	
Instruments	12.99 kg	17.78	2.31	15.30	11.76	
Total Dry(excl.adapter)	112.08			130.11		kg
System margin (excl.adapter)		20.00 %		26.02		kg
Total Dry with margin (excl.adapter)				156.13		kg
Other contributions						
Wet mass contributions						
Adapter mass (including sep. mech.), kg	0.00 kg	0.00	0.00	0.00	0.00	
Total wet mass (excl.adapter)				156.13		kg
Launch mass (including adapter)				156.13		kg

Table 7-4: Rover mass budget

Egress System						
		Target Spacecraft Mass at Launch			50.00	kg
		Below Mass Target by:			28.13	kg
	Without Margin	Margin		Total	% of Total	
Dry mass contributions		%	kg	kg		
Mechanisms	15.78 kg	15.52	2.45	18.23	100.00	
Total Dry(excl.adapter)	15.78			18.23		kg
System margin (excl.adapter)		20.00 %		3.65		kg
Total Dry with margin (excl.adapter)				21.87		kg
Other contributions						
Wet mass contributions						
Adapter mass (including sep. mech.), kg	0.00 kg	0.00	0.00	0.00	0.00	
Total wet mass (excl.adapter)				21.87		kg
Launch mass (including adapter)				21.87		kg

Table 7-5: Egress System mass budget

Although the rover mass slightly exceeds its initial allocation of 150 kg, the total mass for the rover and egress system (178 kg) stays well below the available 200kg available.

7.4.3 Power budget

Table 7-6 provides the power budget per mode. These modes are then individually combined to the references sols as described in section 7.3.3. Note that the duty cycles within the Science Stop Short mode were partially adjusted in different reference sols according to the different respective mode duration per sol.

		Thermal	Loc s/s	Comms	DHS	Mech	GNC	StereoCam	HiResCam	CloseUpCam	OSL	ATR	MeteoPack	Mössbauer	Rob arm	PCDU	TOTAL CONSUMPTION
	Ppeak		76 W			10 W	3.7		10 W	10 W	32 W	10 W	10 W	10 W	5 W		
#1 EDL Mode	Pon	12.45613		0	14 W											4	
	Pstdby	0		0	2 W											1	
	Duty Cycle	30 %		0 %	5 %											100 %	
	Paverage	4 W		0 W	3 W	6.4										4 W	20 W
#2 Deployment Mode	Pon	6.37	32.7	0	14 W											7	
	Pstdby	0		0	2 W											0	
	Duty Cycle	100 %		0 %	100 %											100 %	
	Paverage	6 W		0	14 W	14.75										7 W	42 W
# 3 Traverse Mode	Pon	6.379002	41	3	25 W		2.85						6			7	
	Pstdby	0	0	0	2 W		0						0			0	
	Duty Cycle	0 %	100 %	100 %	100 %		100 %						0 %			100 %	
	Paverage	0 W	40.984	3	25 W		2.85						0 W			7 W	79 W
# 4 Science Stop Short Mode	Pon	6.379002		3	14 W			10	10				10			7	
	Pstdby	6.379002		27	2 W			0	0				0			0	
	Duty Cycle	100 %		100 %	100 %			100 %	100 %				100 %			100 %	
	Paverage	6 W		3	14 W	0	0	10 W	10 W	0	0	0	10 W	0		7 W	60 W
#5 Science Stop Long Mode	Pon	6.379002		3	14	60				8	12	3	6			7	
	Pstdby	6.379002		0	2												
	Duty Cycle	100 %		100 %	100 %	17 %				21 %	63 %	16 %	33 %			100 %	
	Paverage	6.379002		3	14	10.2				1.68	7.5792	0.48	1.98			7	52 W
#6 Science Stop Night Mode	Pon	12.15			14								6	4		4	
	Pstdby	12.15			2												
	Duty Cycle	100 %			100 %								33 %	100 %		100 %	
	Paverage	12.15			14	0.02							1.98	4		4	36 W
# 7 Nominal Night Mode	Pon	12.15		26.4	14 W								6			4	
	Pstdby	0		1.5	2 W								0			0	
	Duty Cycle	100 %		1 %	1 %								0 %			100 %	
	Paverage	12 W		2 W	2 W								0 W			4 W	20 W
# 8 DTE Communications Mode	Pon	4.25		133	14 W	10							6			7	
	Pstdby	0		6.3	2 W	0							0			0	
	Duty Cycle	100 %		14 %	100 %	3 %							33 %			100 %	
	Paverage	4 W		24 W	14 W	0.2857							2 W			7 W	52 W
# 9 Idle Mode Day	Pon	6.37		26.4	14 W								6			7	
	Pstdby	6.3353		3.7	10 W								0			0	
	Duty Cycle	100 %		1 %	1 %								33 %			100 %	
	Paverage	6 W		4 W	10 W								2 W			7 W	29 W
# 10 Hibernation Mode	Pon	14.56724		0	2 W											1	
	Pstdby	14.56724		0	2 W											0	
	Duty Cycle	100 %		0 %	100 %											100 %	
	Paverage	15 W		0 W	2 W											1 W	18 W

Table 7-6: MarsFAST power budget per mode

7.4.4 Equipment List

The equipment lists for the rover and egress system are provided in Table 7-7 and Table 7-8 respectively. The system level harness is not depicted in this breakdown. It is shown in the rover mass budget in Table 7-4.

Element 1 - Rover						
FUNCTIONAL SUBSYSTEM	nr	Mass (kg) per unit	Total Mass (kg)	Margin (%)	Margin (kg)	Mass (kg) with Margin
Structure			**8.42**	**20.00**	**1.68**	**10.10**
Bathtub	1	4.51	4.51	20.00	0.90	5.41
Inserts	1	0.68	0.68	20.00	0.14	0.81
Edge Cap (U-section)	1	0.90	0.90	20.00	0.18	1.08
Doublers	1	0.45	0.45	20.00	0.09	0.54
HDRM Fittings	4	0.30	1.20	20.00	0.24	1.44
Miscellanea	1	0.68	0.68	20.00	0.14	0.82
Thermal Control			**3.48**	**10.72**	**0.37**	**3.85**
Heat Switches (Loop Heat Pipes)	3	0.50	1.50	10.00	0.15	1.65
Radiators	3	0.42	1.25	10.00	0.12	1.37
Insulation	1	0.25	0.25	20.00	0.05	0.30
Filer	1	0.10	0.10	10.00	0.01	0.11
Temperature Sensors	161	0.00	0.32	10.00	0.03	0.35
Heaters	1	0.06	0.06	10.00	0.01	0.06
Mechanisms			**7.93**	**14.16**	**1.12**	**9.05**
HDRM rover (platform)	4	0.30	1.20	20.00	0.24	1.44
HDRM rover (wheels)	6	0.15	0.90	20.00	0.18	1.08
Umbilical release mechanism	3	0.05	0.15	10.00	0.02	0.17
HDRM camera head (mast)	1	0.25	0.25	10.00	0.03	0.28
t Deployment mechanism (tilt actuator)	1	0.50	0.50	5.00	0.03	0.53
HDRM (solar array, 4 panels)	4	0.10	0.40	10.00	0.04	0.44
Deployment (solar array, 4 panels)	4	0.30	1.20	10.00	0.12	1.32
Hinges (solar array, 2 panels)	4	0.30	1.20	10.00	0.12	1.32
HDRM HGA	3	0.25	0.75	20.00	0.15	0.90
Deployment mechanism (pan actuator)	1	0.45	0.45	5.00	0.02	0.47
Corer/grinder (incl. ATR)	1	0.70	0.70	20.00	0.14	0.84
HDRM Robotic Arm	3	0.08	0.23	20.00	0.05	0.27
Communications			**12.20**	**11.23**	**1.37**	**13.57**
DUX	2	1.70	3.40	20.00	0.68	4.08
TWT	2	1.00	2.00	5.00	0.10	2.10
EPC	2	1.50	3.00	5.00	0.15	3.15
HGA	1	1.00	1.00	20.00	0.20	1.20
LGA	2	0.40	0.80	5.00	0.04	0.84
RFDU	1	2.00	2.00	10.00	0.20	2.20
Data Handling			**5.50**	**10.00**	**0.55**	**6.05**
RV OBC	1	5.50	5.50	10.00	0.55	6.05
GNC			**1.80**	**14.44**	**0.26**	**2.06**
NavCam	2	0.20	0.40	10.00	0.04	0.44
LocCam	2	0.20	0.40	10.00	0.04	0.44
IMU	2	0.30	0.60	20.00	0.12	0.72
Sun Sensor	1	0.20	0.20	20.00	0.04	0.24
HazCam	1	0.20	0.20	10.00	0.02	0.22
Robotics			**25.87**	**18.66**	**4.83**	**30.70**
Wheel	6	1.15	6.92	20.00	1.38	8.31
Driving actuator	6	0.45	2.70	20.00	0.54	3.24
Steering actuator	6	0.35	2.10	15.00	0.32	2.42
Side bogie beam	2	1.00	2.00	20.00	0.40	2.40
Rear bogie beam	1	1.00	1.00	20.00	0.20	1.20
Harness	1	1.04	1.04	10.00	0.10	1.15
Motion controller	36	0.21	7.38	20.00	1.48	8.86
Deployment actuator	6	0.45	2.72	15.00	0.41	3.13
Power			**27.70**	**20.00**	**5.54**	**33.24**
Solar Array	1	16.00	16.00	20.00	3.20	19.20
Battery	1	4.70	4.70	20.00	0.94	5.64
PCDU	1	7.00	7.00	20.00	1.40	8.40
Instruments			**12.99**	**17.78**	**2.31**	**15.30**
StereoCam	*1*		*1.50*	*20.00*	*0.30*	*1.80*
Eye 1	1	0.65	0.65	20.00	0.13	0.78
Eye 2	1	0.65	0.65	20.00	0.13	0.78
E-board	1	0.20	0.20	20.00	0.04	0.24
HiResCam	*1*		*1.00*	*20.00*	*0.20*	*1.20*
camera head	1	1.00	1.00	20.00	0.20	1.20
CloseUpCam	*1*		*1.00*	*20.00*	*0.20*	*1.20*
camera	1	1.00	1.00	20.00	0.20	1.20
OSL	*1*		*2.50*	*20.00*	*0.50*	*3.00*
OSL instrument	1	2.00	2.00	20.00	0.40	2.40
E-boards	2	0.25	0.50	20.00	0.10	0.60
ATR	*1*		*0.50*	*20.00*	*0.10*	*0.60*
ATR	1	0.50	0.50	20.00	0.10	0.60
MeteoPack	*1*		*3.00*	*20.00*	*0.60*	*3.60*
Boom+instruments	1	2.50	2.50	20.00	0.50	3.00
E-boards	1	0.50	0.50	20.00	0.10	0.60
Mössbauer	*1*		*0.60*	*20.00*	*0.12*	*0.72*
instrument head	1	0.50	0.50	20.00	0.10	0.60
E-board	1	0.10	0.10	20.00	0.02	0.12
Robotic arm	*1*		*2.89*	*10.00*	*0.29*	*3.18*
Robotic arm	1	2.89	2.89	10.00	0.29	3.18

Table 7-7: Rover equipment list

Element 2 - Egress System						
FUNCTIONAL SUBSYSTEM	nr	Mass (kg) per unit	Total Mass (kg)	Margin (%)	Margin (kg)	Mass (kg) with Margin
Mechanisms			**13.78**	**15.45**	**2.13**	**15.91**
Ramp (size #1)	8	0.70	5.60	20.00	1.12	6.72
Ramp (size #2)	4	0.20	0.80	20.00	0.16	0.96
Hinge (type #1)	4	0.80	3.20	10.00	0.32	3.52
Hinge (type #2)	4	0.40	1.60	10.00	0.16	1.76
Hinge (type #3)	0	0.40	0.00	10.00	0.00	0.00
0.00	0	0.00	0.00	0.00	0.00	0.00
HDRM (support structure #2)	2	0.80	1.60	20.00	0.32	1.92
HDRM (NEA 9100)	14	0.07	0.98	5.00	0.05	1.03

Table 7-8: Egress System equipment list

8 CONFIGURATION

8.1 Requirements and Design Drivers

- MarsFAST rover and its egress system shall fit inside the NASA provided envelope as shown below:

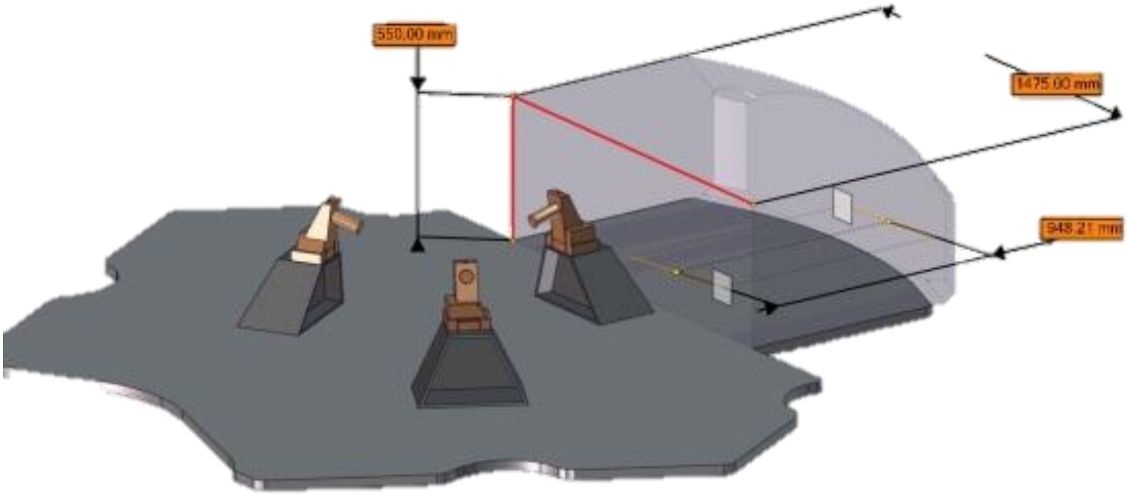


Figure 8-1: MarsFAST envelope on the SKYCRANE palette

- MarsFAST rover shall constitute following deployment sequence:
  a. Deployment of the egress system
  b. Deployment of solar panels
  c. Deployment of camera mast
  d. Release of rover HDRM
  e. Deployment of the boogies of the locomotion system to lift the rover to stand-up position
- Rover shall accommodate subsystem units according to their requirements.
- Locomotion stowed dimension drives the maximum envelope of the rover body.

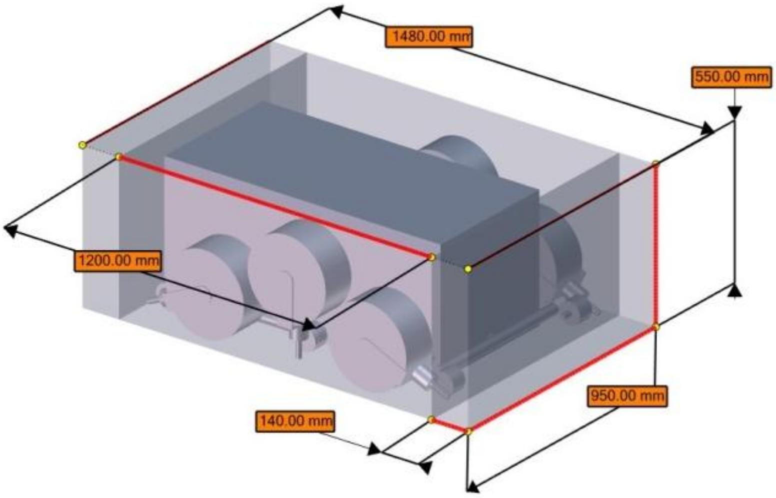


Figure 8-2: Maximum available volume for the Rover body and egress system

8.2 Assumptions and Trade-Offs

During the first iteration, the following assumptions were used to design the MarsFAST rover:

- Skycrane palette can be customised to have direct egress system.

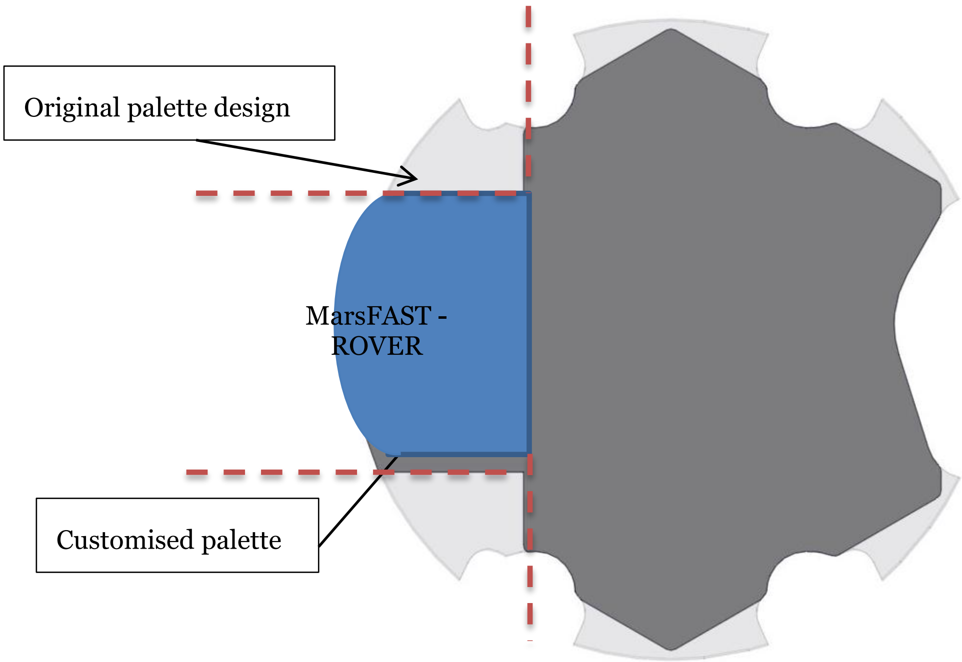


Figure 8-3: Customised palette design

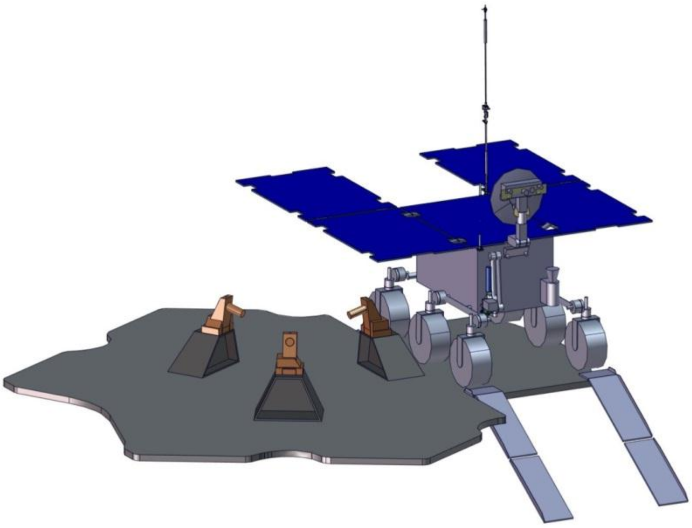


Figure 8-4: Rover direct egress

- 30mm height used to accommodate the Rover HDRMs located between bottom part of the rover body and the palette.

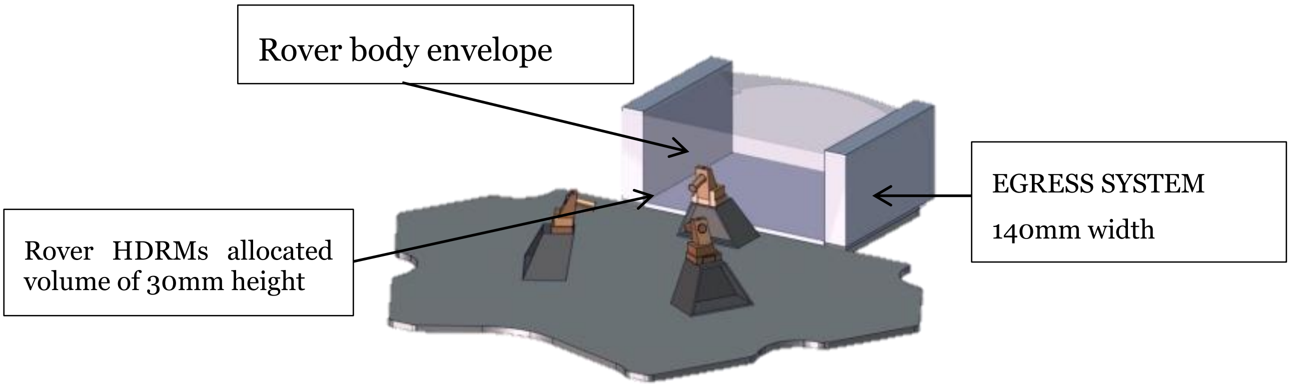


Figure 8-5: MarsFAST rover inside the given envelope

8.3 Baseline Design

The locomotion system is connected to the rover body in 3 locations shown in Figure 8-6. This interface location drives the rover body bottom part dimension of 790mm by 500mm (see chapter 8.4). 5 layers of solar panels are placed on top of the rover body. The area of the rover top part is larger than the bottom part to support the solar panels stack namely 910mm by 500mm (see chapter 8.4). Front part of the rover accommodates robotic arm, OSL payload, camera mast assembly and LGA. Meteo Pack assembly, hazard camera and LGA are located on the back side of the rover. Camera mast supports three different cameras: stereo-, navigation- and high resolution camera. The mast supports also the HGA of 35cm diameter.

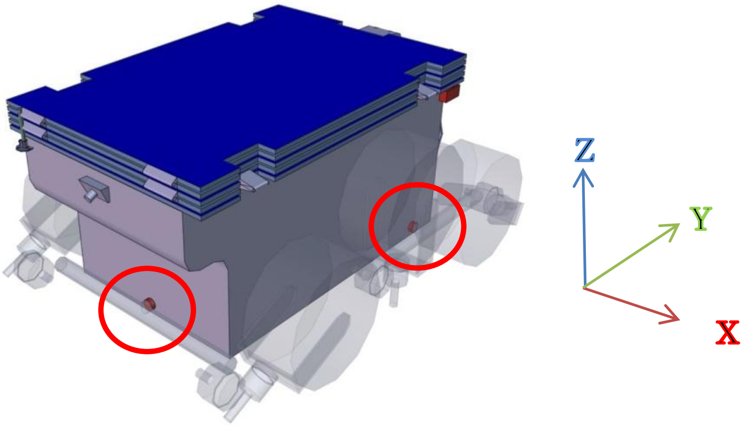


Figure 8-6: 3 IF points between Rover and the Locomotion system (one point located on negative X is not shown)

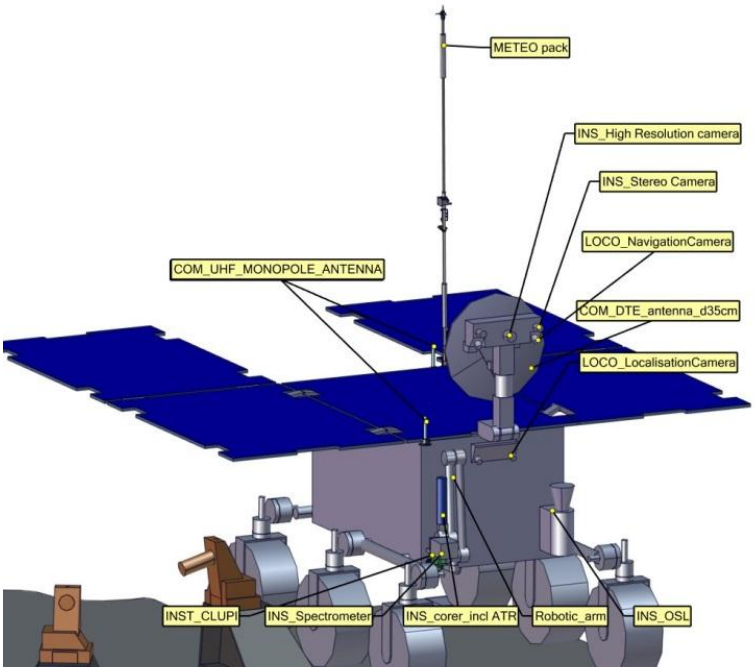


Figure 8-7: External accommodation (front section)

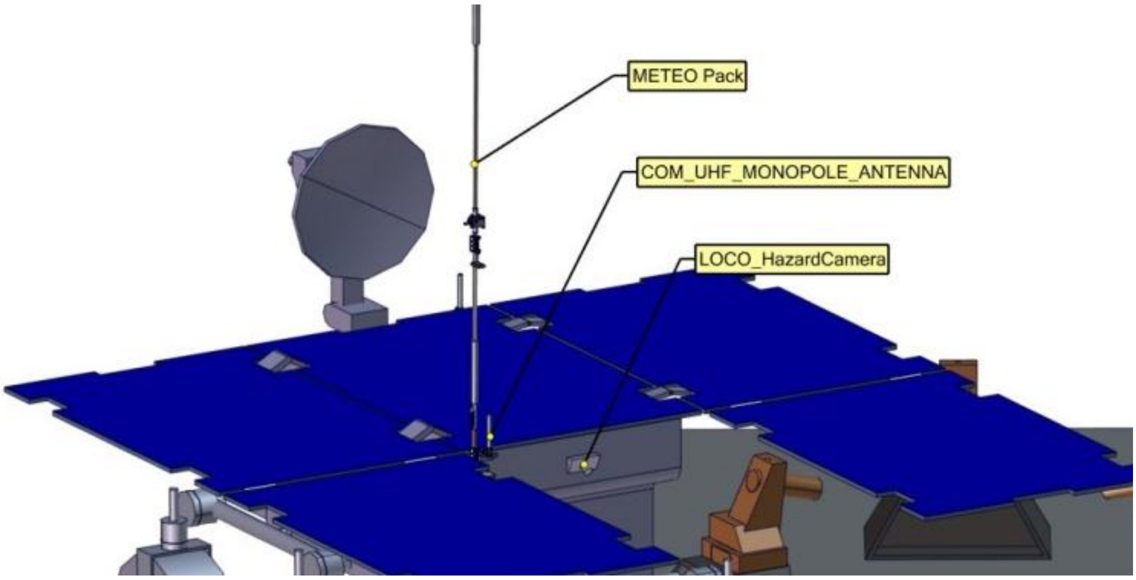


Figure 8-8: External accommodation (rear section)

Figure 8-9 shows that electronic boxes are mounted on a U-shaped structural panel for easy access during integration.

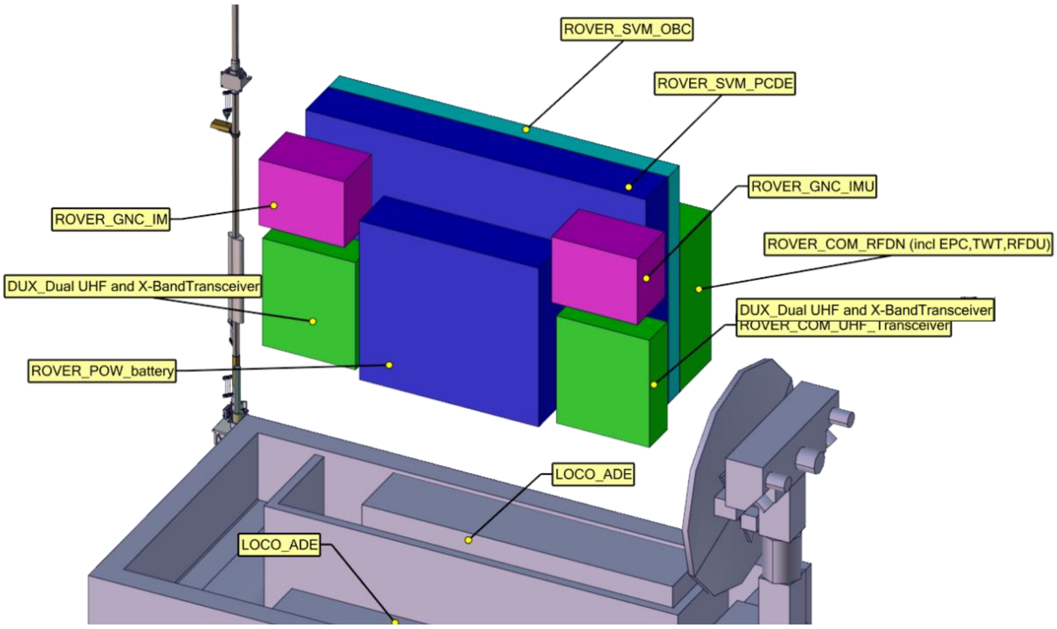


Figure 8-9: Internal accommodation of the rover

8.4 Overall Dimensions

Figure 8-10 to Figure 8-14 show the overall dimension of the MarsFAST rover in stowed- and deployed configuration. All dimensions displayed here are in mm.

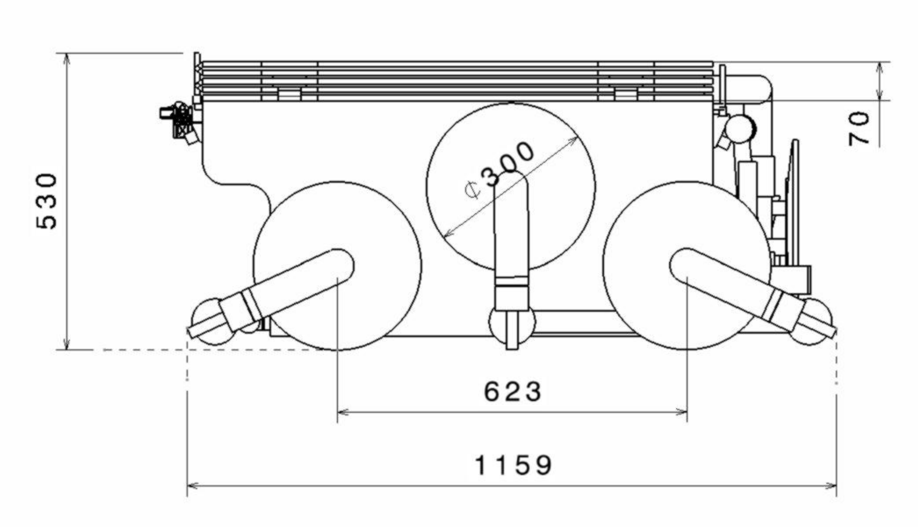


Figure 8-10: Overall dimension – stowed configuration - side view

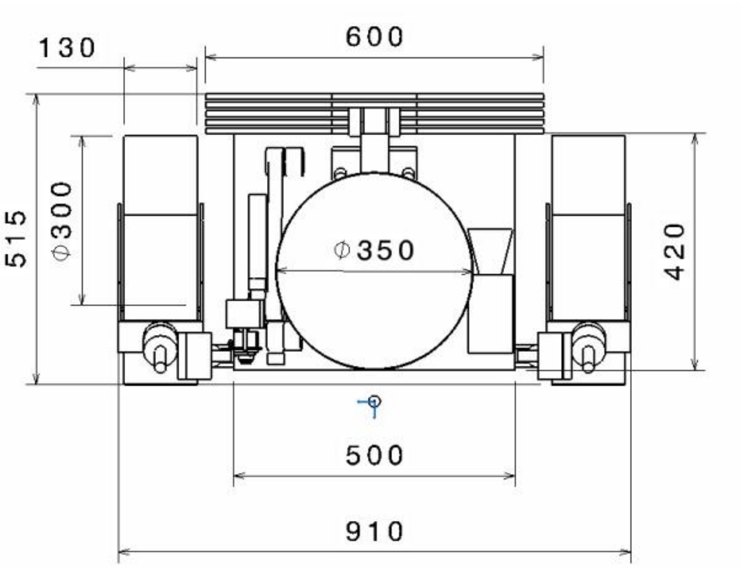


Figure 8-11: Overall dimension– stowed configuration - front view

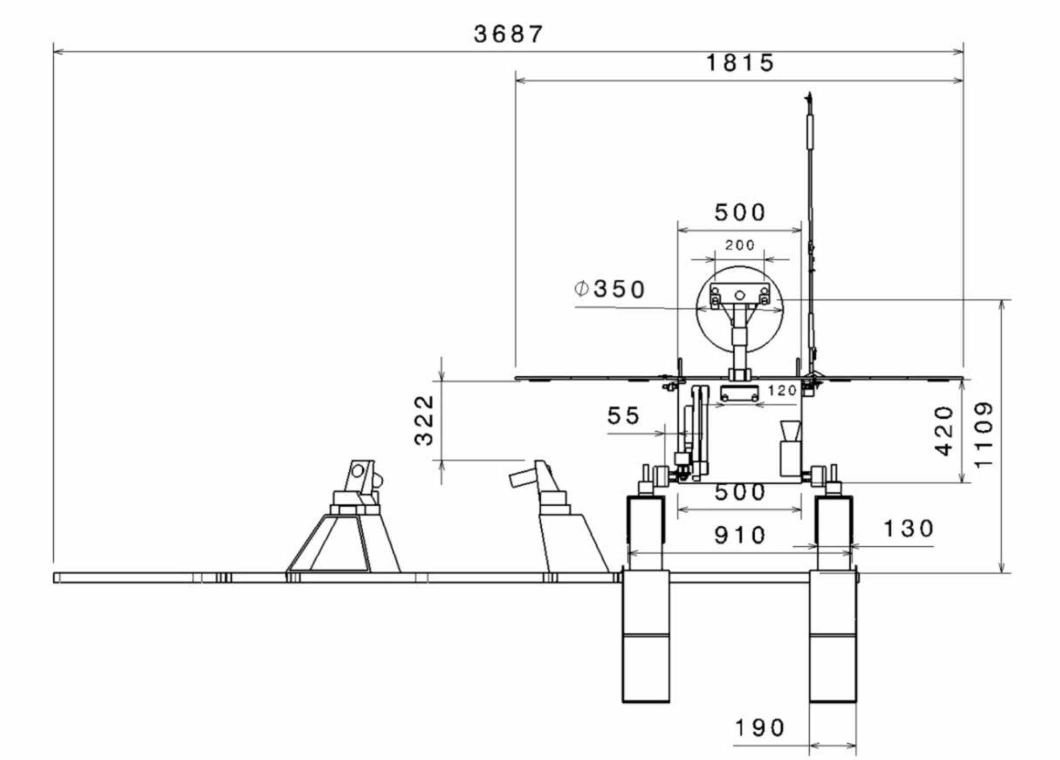


Figure 8-12: Overall dimension– deployed configuration - front view

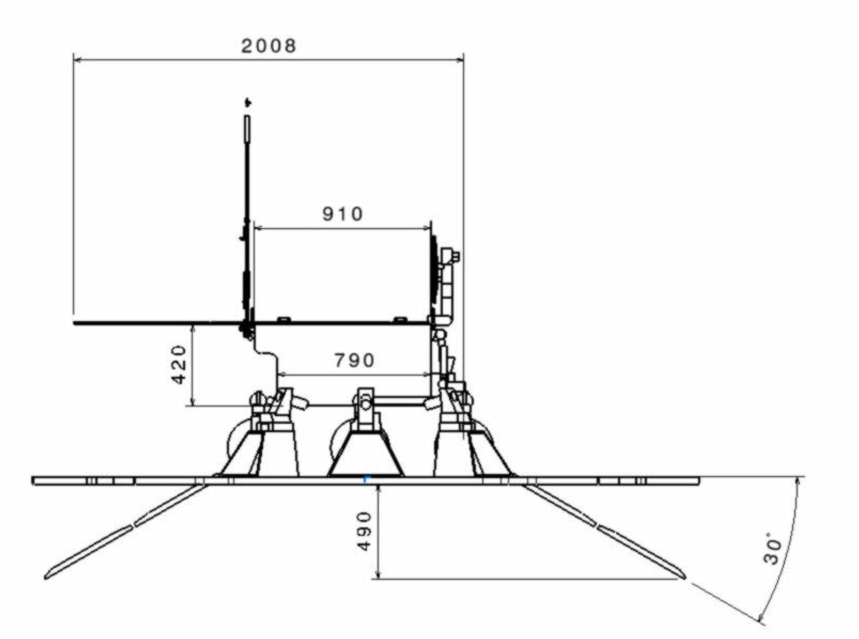


Figure 8-13: Overall dimension– deployed configuration – side view

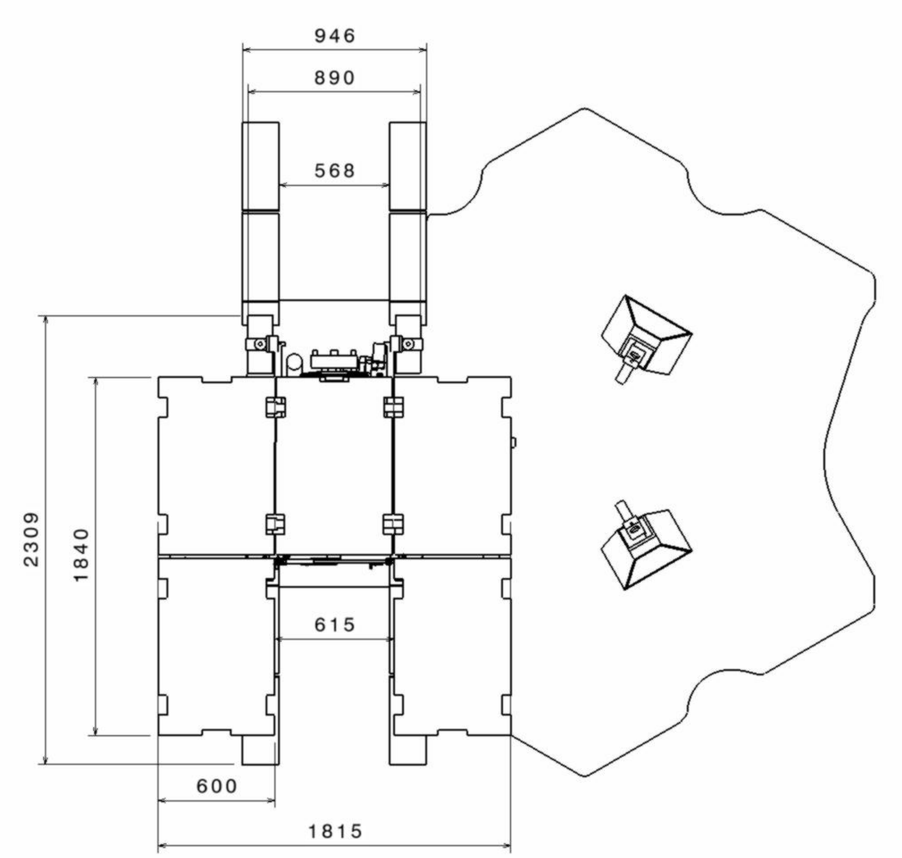


Figure 8-14: Overall dimension– deployed configuration – top view

9 STRUCTURES

9.1 Requirements and Design Drivers

For the proposed design of the MarsFAST Rover structure, no specific requirements have been specified.

As a result of a preliminary trade-off, with reference to heritage studies (e.g. Sample Fetch Rover (SFR) industrial studies and MarsREX CDF), a preliminary allocation of 19 kg (16% share) has been proposed for the structure of the MarsFAST rover.

9.2 Assumptions and Trade-Offs

The proposed configuration of the structure of the Rover was mainly driven by the heritage of previous studies (SFR, MarsREX) and by general configuration needs.

9.3 Baseline Design

The primary load path of the Rover, the Rover Body, is a monolithic piece of composite sandwich moulding with CFRP faceskins and glass fibre reinforced plastic (GFRP) honeycomb core.

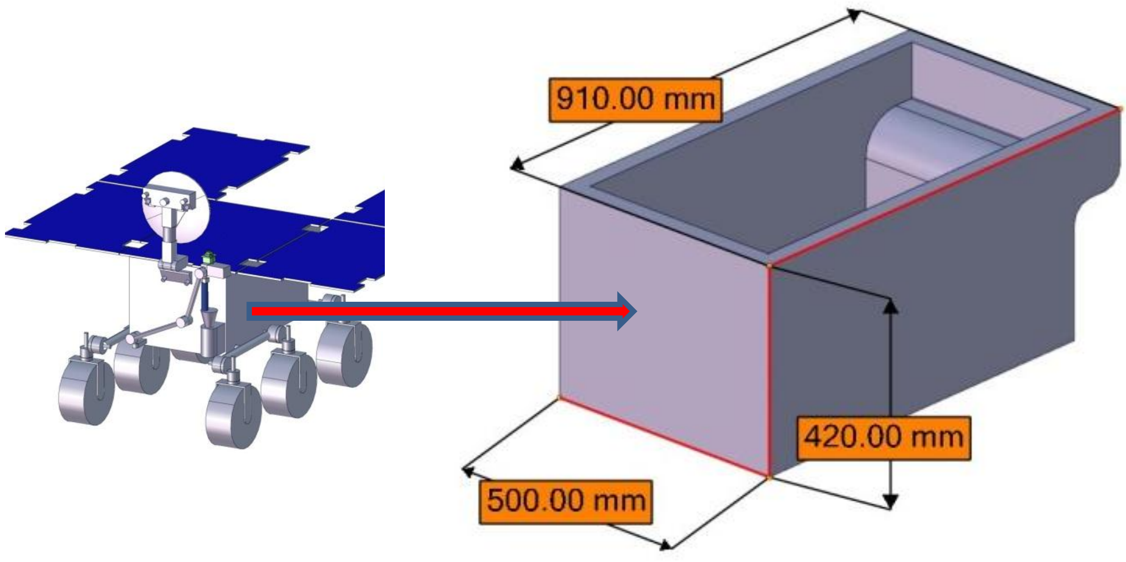


Figure 9-1: MarsFAST Rover Body

M40J carbon fibres are selected for the face-skins. The laminates (orientation: [0,45-45,90]) are quasi-isotropic lay-ups in a cyanate-ester resin system.

The core is a GFRP honeycomb type HRP-3/16-4.0 with a thickness of 15mm.

The use of additional doubler plies, co-cured to the inner and outer skins, is foreseen to reinforce the load input and stress concentration areas of the structure.

The upper edge of the body is closed out by moulded CFRP U-section edge capping which provides an interface for the deployable solar panels.

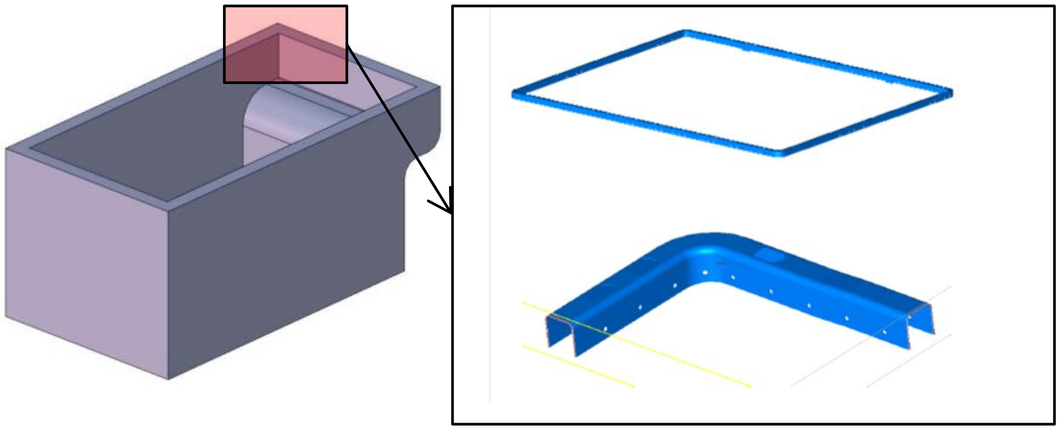


Figure 9-2: Rover Body Edge Capping

Equipment interfaces (e.g. locomotion system, service module, etc) are provided by potted aluminium alloy inserts installed in the walls of the body.

9.3.1 Rover Body Mass Budget

The estimated mass budget of the Rover Body is given in the following table:

Unit	Mass [Kg]	Unit Margin	Mass [Kg] (incl.margin)
Body	4.51	20%	5.41
Edge Cap	0.90	20%	1.08
Doublers	0.45	20%	0.54
Inserts	0.68	20%	0.81
HDRMs Fittings (x4)	1.2	20%	1.44
Miscellanea	0.68	20%	0.82
	8.42		**10.1**

Table 9-1: Rover Body Mass Budget

9.4 Technology Requirements

For the structure subsystem of the MarsFAST Rover, no special technological developments needs have been identified in the frame of this study. The proposed solution and the assessment performed during the study are based on mature and “flight proven” (TRL9) technology.

10 MECHANISMS

This subsystem includes all mechanisms for the rover as well as the egress system.

10.1 Rover Structure and Locomotion Subsystem HDRMs

This section includes hold down and release mechanisms (HDRMs) for the rover body, the wheels and the umbilical connections.

10.1.1 Requirements and Design Drivers

SubSystem requirements		
Req. ID	**STATEMENT**	**Parent ID**
MEC-010	Mechanisms shall withstand the loads during all critical phases of the mission with a particular emphasis on the launch and landing phases.	

10.1.2 Assumptions and Trade-Offs

- Non-explosive actuators (NEA) should be applied due to their capability to generate relatively low shock during actuation (in comparison with pyro devices). Moreover NEAs have low mass, small volume and a significant heritage in space applications.
- QS loads for sizing are based on the following assumptions:
- For large equipment the descent and landing loads were assumed to dominate and were assumed to be 40g in axial and radial directions (provided by the study client referring to Inspire mission with airbag based landing, which is probably conservative compared to parachute and sky crane landing).
- For egress ramps the launch loads input may exceed this value and for this sizing 50g quasistatic load in all directions was assumed.

10.1.3 Baseline Design

HDRM design is based on TiNi Aerospace frangibolts and NEA Electronics non-explosive actuators. The Frangibolt actuator is using a titanium-nickel shape memory alloy (SMA) body which when heated above its phase transition temperature (~90°C) by integral electrical heaters expands and fractures the notched titanium bolt (Figure 10-1). The actuator incorporates prime and redundant heater circuits. The NEA HDRM is an electrically initiated, one-shot release mechanism that has the ability to carry a very high tensile preload until commanded to release. The preload is applied through a release rod held in place by two separable spool halves which are in turn held together by tight winding of restraining wire. The restraint wire is held in place by redundant electrical fuse wires; actuation of either circuit allows release, assuring maximum reliability. When sufficient electrical current is applied, the restraint wire unwinds allowing the spool halves to separate releasing the release rod and the associated preload.

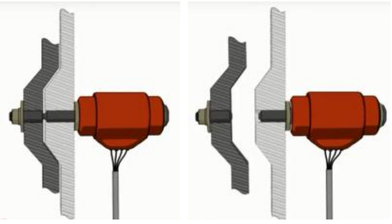


Figure 10-1: TiNi Aerospace Frangibolt concept

10.1.3.1 Body HDRMs

The rover body is attached in the corners at discrete hold-down points by 4 bipod supports. These are arranged such that the normals to the planes through each bipod pass through a common central point to provide an iso-static (or kinematic) mounting system. This minimises constraint loads at the interface arising from differential strains between the Rover and Lander at separation. Each bipod provides constraints in the vertical and tangential translational degrees of freedom. 3 bipods would provide a true iso-static mounting system (6 DOFs constrained), however the 4 point arrangement has been baselined because the 2 front corner bipods provide a stiff support to the side bogie pivots and because of the difficulty in accommodating the 3rd bipod interface at the rear close to the rear bogie telescopic deployment mechanism.

Each hold-down interface comprises a mating cup & cone clamped (Figure 10-2). The actuator is mounted on the lander side of the separating interface. The cup & cone permits the transfer of shear loads and local moments without overloading the frangibolt.

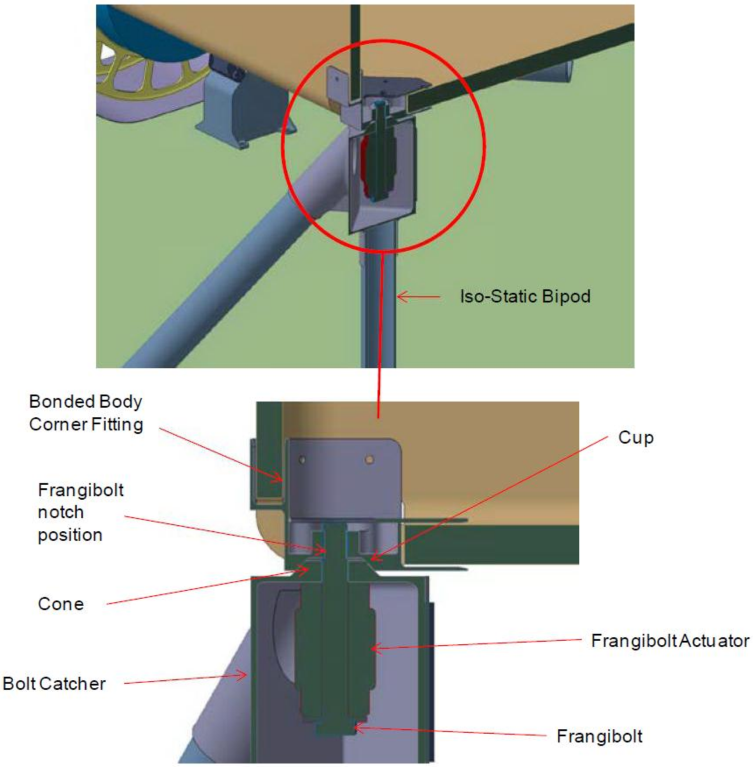


Figure 10-2: MarsFAST's HDRM

Based on the following calculations FC8 actuator (Figure 10-3) rated for 44kN release load from Ti-Ni Aerospace has been chosen for the rover's body.

Rover body HDRM calculations		
Rover mass	150.00	[kg]
QL loads axial and radial directions	40.00	[g]
Number of HDRM points used	4.00	[]
Force acting on the single HDRM mechanism during descent and landing	32903.74	[N]

Table 10-1: Rover body HDRMs calculations

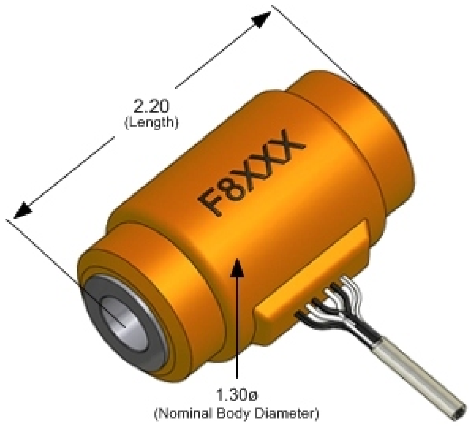
Actuator FC8

The FC8 is designed to operate with any standard high strength 1/2" notched fastener[1]. The Nitinol (Shape Memory Alloy) cylinder generates 15,000 lbs of force to fracture the fastener in tension during actuation. The FC8 is suitable for applications which require up to 10,000 lbf of load holding capability.

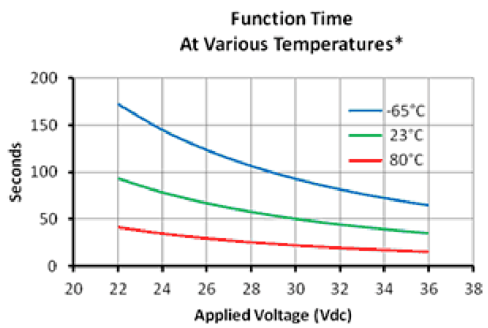
Features:

- Redundant firing circuit
- High fatigue life with minimum 60 cycles
- Simple manual reset
- Embedded RTD for temperature monitoring

[1] TiNi Aerospace must provide the specially notched Titanium fastener. This is largely application dependent and is readily manufactured to customer specification.



*Contact TiNi for detailed specification.



*Nominal values for estimation purposes only. Actual function time depends on application (joint) design and circuit used (primary or secondary).

Mass:	5.1 oz (145 g)
Power:	140 W @ 28 VDC
Operational Voltage:	28 - 41 VDC
Current Draw:	5 A @ 28 VDC
Resistance:	7.5 ± 1.0 Ω
Bolt Tensile Strength:	Typical 15,000 lbf (66,723 N)
Max Load Support and Release:	10,000 lbf (44,482 N)
Function Time:	Typical 72 sec. @ 28 VDC
Reusable:	By Re-Compressing Actuator
Life:	60 Cycles MIN
Operational:	-65° C to +80° C

*Specification subject to revision; Please contact TiNi Aerospace for detailed drawing (ICD).

Figure 10-3: FC8 Frangibolt

10.1.3.2 Wheels HDRMs

- Wheels HDRMs were calculated for the mass of the locomotion system
- HDRMs for the middle wheels connect them to the rover body (due to the locomotion subsystem limitations in stowed configuration).

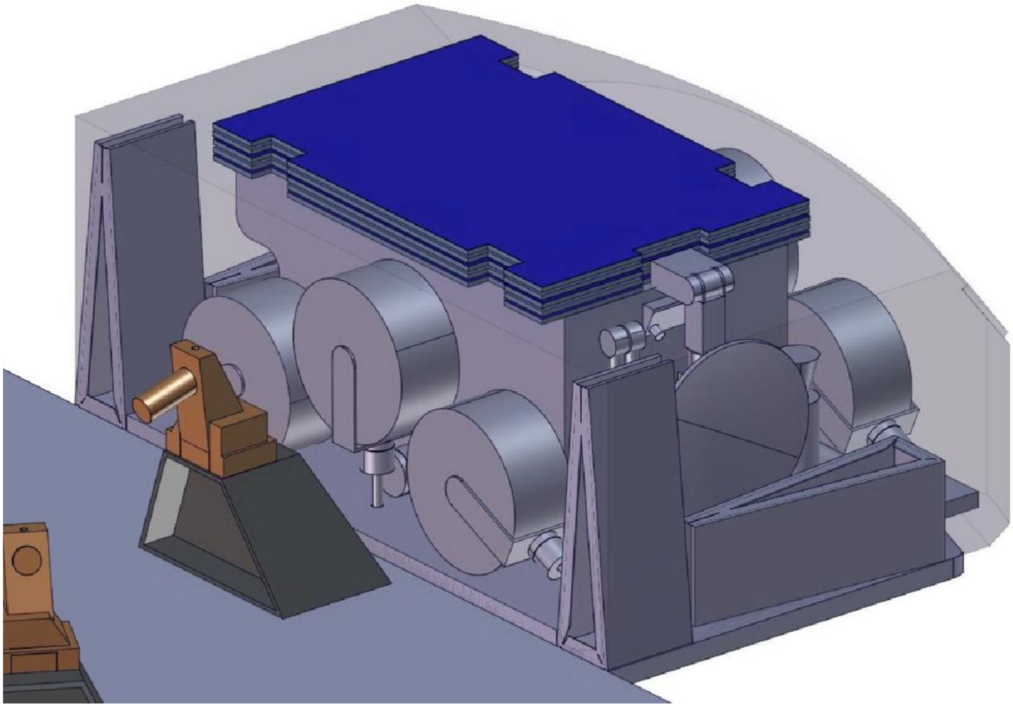


Figure 10-4: MarsFAST rover and egress system in the stowed configuration

The locomotion subsystem bogies are free to rotate about the pivot attachment points on the rover's body so hold-downs are necessary to constrain this motion in the stowed configuration and offload the drive and steering actuator bearings.

Six HDRMs have been chosen. Front and rear wheel HDRMs that connect the rover wheels to the platform (4 units in total), were based on Sample Fetching Rover (SFR) design. Middle wheel HDRMs connect the wheel to the rover body.

Each hold-down interface comprises a cone on the lander/rover body bracket clamped into a mating recess in the bottom of each wheel support leg by a frangibolt passing through a TiNi Aerospace frangibolt actuator, identical to those used for the body. The cone axis is aligned at 45° to the vertical to permit the wheel leg to separate horizontally as the telescopic bogie beams are extended. The front wheel hold-down cone axes are inclined 'forwards' and the rear wheel hold-down cone axes 'aft' to permit the forwards and aft extensions of the respective bogies.

An alternative wheel hold-down interface is shown in Figure 10-6. This also utilises a frangibolt clamping together a cup-cone, but in this design the HDRM is threaded into a ball joint on the wheel leg, which permits it to rotate freely (over a few degrees) about any axis. The objective is to minimise local moments at the interface, which are the main driver on the size of the cup-cone contact. The cup-cone and overall size of the interface can therefore be reduced to increase the subsequent clearance during rover egress.

In both concepts, the frangibolt notch is within the conical cup on the wheel leg, so the broken part of the bolt does not protrude below the leg during surface operations. The actuator and other part of the bolt fall into the lander bracket cavity. A closure plate over this cavity provides containment.

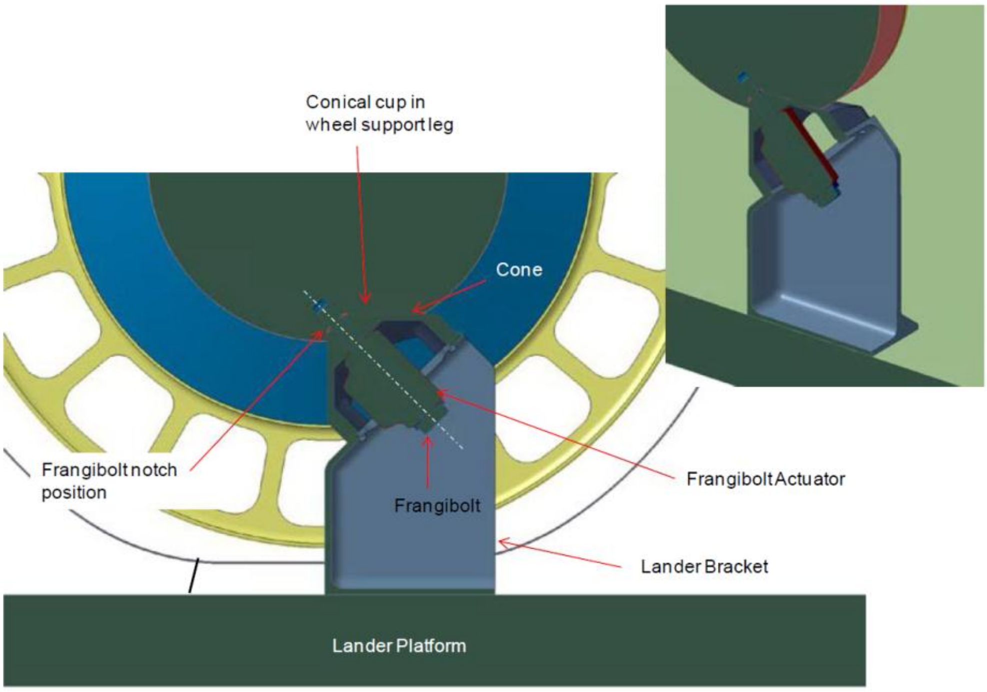


Figure 10-5: Front / rear wheel MarsFAST's HDRMs

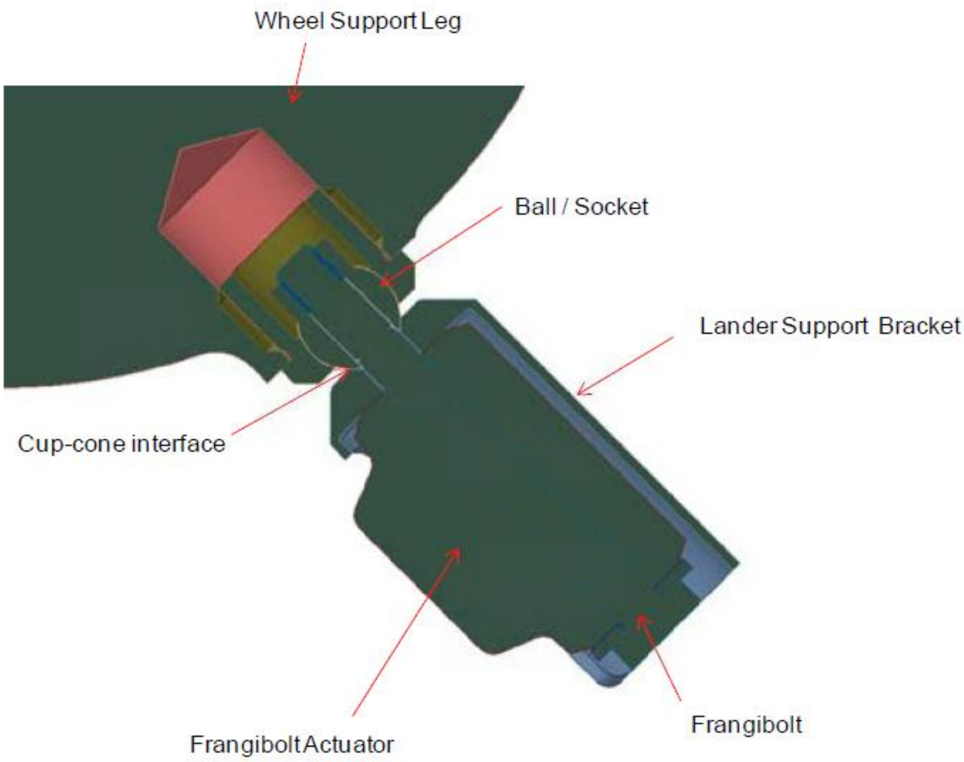


Figure 10-6: Alternative front / rear wheel MarsFAST's HDRMs design

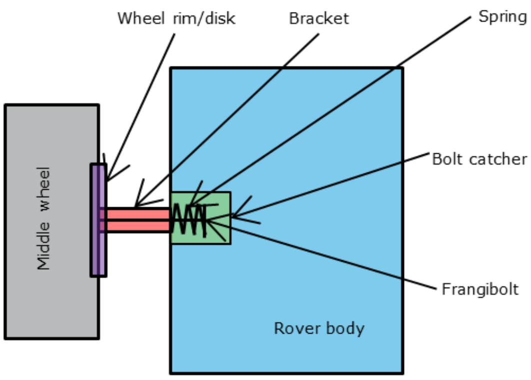


Figure 10-7: Schematic design of the middle wheels HDRMs

Based on the following calculations Frangibolt FC3 has been chosen for the rover wheels HDRMs.

Rover wheel HDRM calculations		
Wheel mass	5.2	[kg]
QS load in axial and radial direction	40.00	[g]
Number of HDRM points used (n)	1.00	(per wheel)
Force acting on the single HDRM mechanism during descent and landing	2964.02	[N]

Table 10-2: Rover wheels HDRMs calculations

10.1.3.3 Lander/Rover Umbilical Cord Release Mechanisms

Frangibolt FC2 (Figure 10-8) based HDRM was chosen based on the following calculations.

Umbilical HDRM calculations		
Connectors' mass (m)	0.50	[kg]
QS load in axial and radial direction	40.00	[g]
Number of HDRM points used (n)	1.00	(per connector)
Force acting on the single HDRM mechanism during launch	285.00	[N]

Table 10-3: Umbilical Release Mechanisms calculations

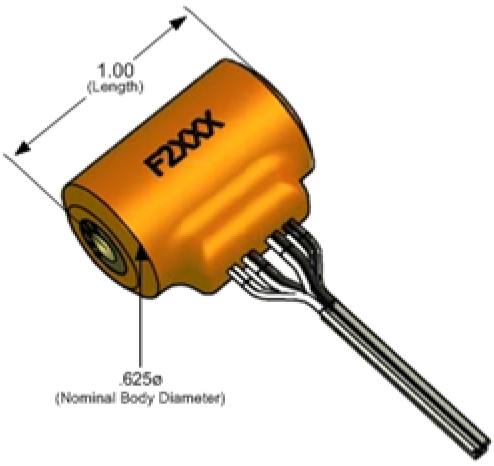
Actuator FC2

The FC2 is designed to operate with any standard high strength #8 size notched fastener.[1] The Nitinol (Shape Memory Alloy) cylinder generates 1,400 lbs of force to fracture the fastener in tension during actuation. The FC2 is suitable for applications which require up to 500 lbf of load holding capability.

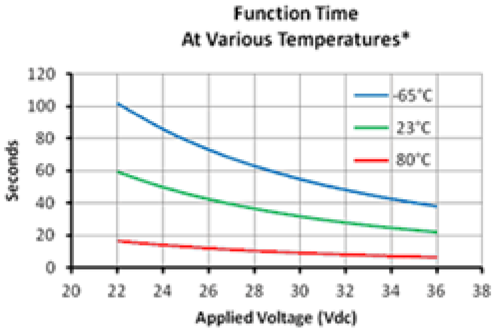
Features:

- Redundant firing circuit
- High fatigue life with minimum 60 cycles
- Simple manual reset
- Embedded RTD for temperature monitoring

[1] TiNi Aerospace must provide the specially notched Titanium fastener. This is largely application dependent and is readily manufactured to customer specification.



*Contact TiNi for detailed specification.



Mass:	0.7 oz (20 g)
Power:	25 W @ 28 VDC
Operational Voltage:	22 - 34 VDC
Current Draw:	0.9 A @ 28 VDC
Resistance:	31 ± 3.0 Ω
Bolt Tensile Strength:	Typical 1,000 lbf (4,448 N)
Max Load Support and Release:	500 lbf (2,224 N)
Function Time:	Typical 32 sec. @ 28 VDC
Reusable:	By Re-Compressing Actuator
Life:	60 Cycles MIN
Operational:	-65° C to +80° C

Figure 10-8: Frangibolt FC2

10.2 Camera Mast and High Gain Antenna HDRMs

10.2.1 Requirements and Design Drivers

Section 10.1.1 is applicable.

10.2.2 Assumptions and Trade-Offs

Section 10.1.2 is applicable

10.2.3 Baseline Design

HDRMs for Camera head and HGA are based on NEA Electronics Model 9100 actuators. NEA 9100 actuator is a non-explosive, low shock and electrically initiated release mechanism. The preload is applied through a release rod held in place by two separable spool halves which are in turn held together by tight winding of restraining wire. The wire is held in place by redundant electrical fuse wires. When sufficient electrical current is applied, the restraint wire breaks allowing the spool halves to separate releasing the release rod and the associated preload.

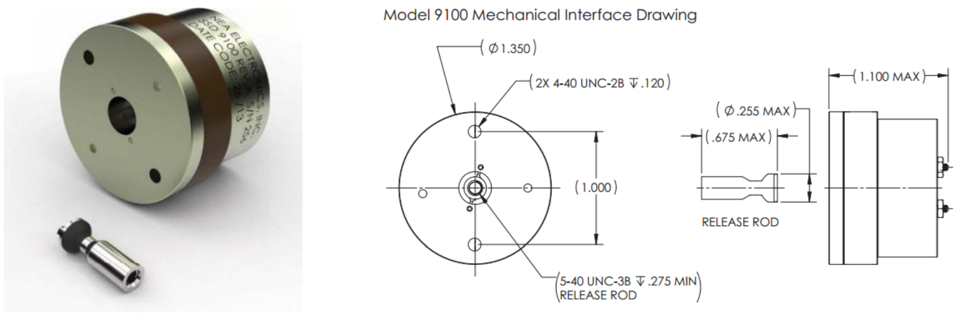


Figure 10-9: NEA 9100 HDRM

10.2.3.1 Camera Head/Mast/High Gain Antenna HDRMs

The NavCam and High Gain Antenna are mounted on a pan & tilt mechanism at the top of a short deployable mast. For stowage, the mast is folded down on the centreline of a front rover body structure and protected by dust cover cups on the hold down bracket. Both mast design and HDRM are based on a Sample Fetching Rover design RD[17] – it includes iso-static holding bracket with a single NEA actuator.

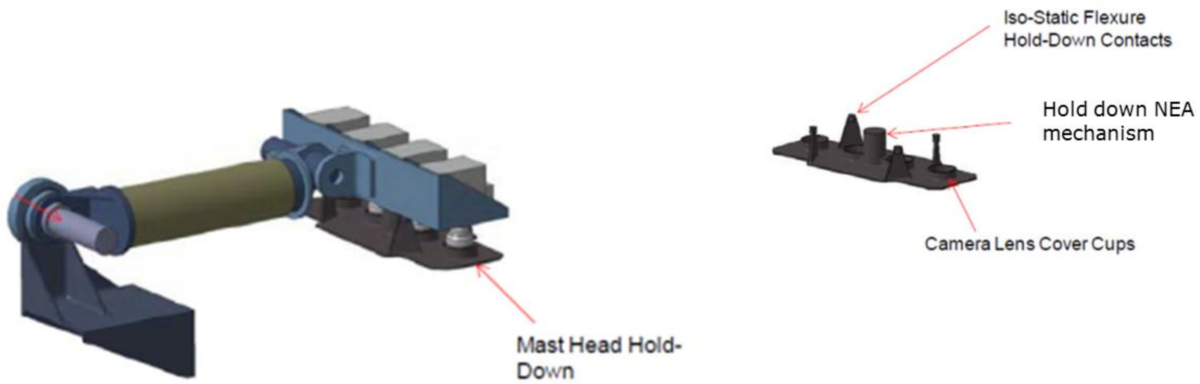


Figure 10-10: Camera head/mast HDRM

HGA HDR design is based on 3 NEA 9100 actuators (Figure 10-12) installed in a triangular pattern.

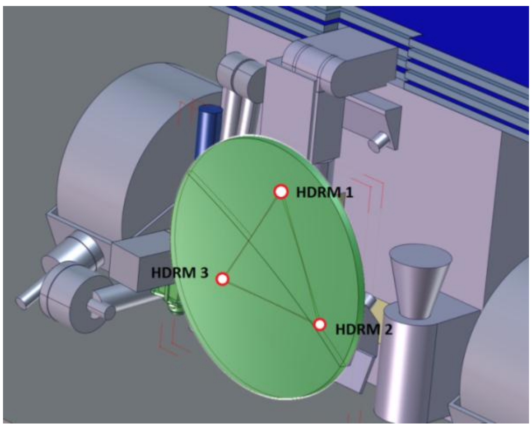


Figure 10-11: HGA HDRM

Based on the following calculations NEA actuators 9100 (Figure 10-12) have been chosen for the described HDRMs.

Mast/HGA HDRMs calculations		
Mast mass with the additional equipment	4.00	[kg]
Acceleration	40.00	[g]
Number of HDRM points used (n)	3.00	[]
Force acting on the single HDRM mechanism during descent and landing	1227.02	[N]

Table 10-4: Mast & HGA HDRMs calculations

Parameter	Capability
Ultimate Load Rating	8 kN (1,800 lbf)
Proof Load Rating	7.6 kN (1,700 lbf)
Release Load Rating	6 kN (1,360 lbf)
Shock @ Preload[1]	<300 g's @ 6 kN (1,360 lbf)
Fuse Wire Resistance	1.2 to 2.0 Ω @ 25°C
Actuation Current[2]	4 Amps for 25 ms
No-Fire Current[3] (continuity)	250 mA
Release Time[4]	<50 ms
Qualification Temperature Range[5]	-135°C to +135°C
Maximum Angular Misalignment	6° Cone
Mass[6]	70 g (0.15 lb)

Notes:
[1]Shock is preload dependent, contact applications engineering for shock at other preloads.
[2]Actuation can be achieved using a range of current, the value in the table is the value used for qualifying this device.
[3]No-fire current for 5 minutes or less as ambient temperature, consult NEA applications engineers for other no-fire current requirements.
[4]Release time is dependent on actuation current, contact applications engineering for more specific information on actuation time as a function of current.
[5]The values presented for qualification temperature range are not a measure of the limits of the device.
[6]Mass does not include harnessing and lead wires.

Figure 10-12: NEA Model 9100 Technical Specifications

10.2.3.2 Mast Deployment and Camera/HGA Pointing Mechanism

A pan/tilt actuator for antenna and camera pointing is required. The camera and antenna is located on the mast which is stowed on the rover body and is deployed after landing.

In principle the tilt actuator could be located on the interface between rover body and the mast and provide both deployment and tilt function. This would, however, mean that the deployment/tilt actuator would have to keep the mast raised and held in position coping with the loads originating from robot driving operations. The driving loads would backdrive the actuator unless countinuously powered-on which is not feasible from energy point of view.

Therefore a decision has been made to put the antenna pointing actuator on top of the mast and include a separate deployment actuator on the bottom of the mast. The deployment actuator will latch in the end position requiring no further power to keep the mast in the deployed position.

The antenna tip/tilt actuator is also the camera head pointing actuator.

The actuators used on NASA Mars Exploration Rovers offer viable solution for mast deployment and antenna /camera pointing (RD[21]). The elevation stage actuator from Table 10-5 was assumed for the mast deployment axis.

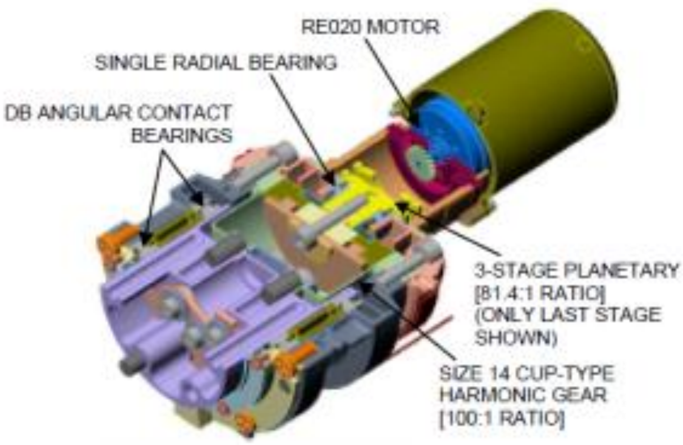


Figure 10-13: MER actuator design example

	Azimuth	Elevation	Elbow	Wrist	Turret
Gear Reduction Type	3-Stage Planetary/ Size 14 Harmonic	3-Stage Planetary/ Size 14 Harmonic	3-Stage Planetary/ Size 11 Harmonic	5-Stage Planet-ary	5-Stage Planet-ary
Gear Ratio	8137:1	8137:1	8137:1	1528:1	1528:1
Total Range of Motion [rad]	2.75	1.25	5.10	5.85	5.95
Static Torque Capability [Nm]	65	65	40	17	28
Operational Output Torque Capability[1] [Nm]	45	45	20	9	9
No-load Speed +23ºC, 28V [rad/s]	0.12	0.12	0.12	0.61	0.61
No-load Speed –70ºC, 28V [rad/s]	0.09	0.09	0.09	0.58	0.58
No-load Current +23ºC [A]	0.03	0.03	0.03	0.03	0.03
No-load Current –70ºC [A]	0.16	0.16	0.12	0.05	0.05
Torque/Current Slope +23ºC [Nm/A]	180	180	180	33	33
Torque/Current Slope –70ºC [Nm/A]	140	140	140	33	33
No-load Mechanical Accuracy[2] [rad]	0.0015	0.0015	0.0020	0.012	0.012
Min. Stop and Hold Torque [Nm]	28	28	20[3]	5.6	3
Motor Detent Torque Strength [mNm]	6[4]	6[4]	6[4]	6[4]	2
Mass [g]	590[5]	480[5]	405	380	350

Table 10-5: Overview of selected MER actuators technical data

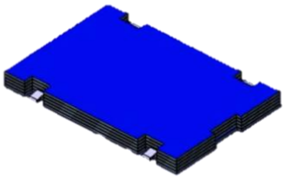
10.3 Solar Array Mechanisms

10.3.1 Requirements and Design Drivers

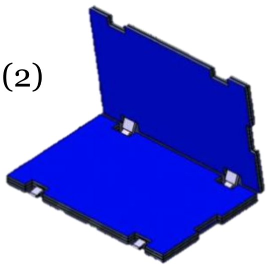
Section 10.1.1 is applicable. Moreover:

- Deployment sequence (Figure 10-14) requires motorised hinges

(1)



(2)



(3) (4)

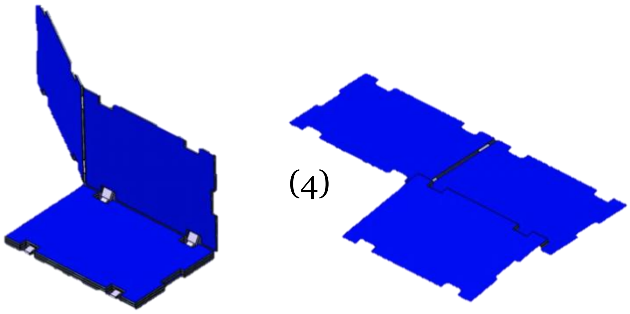


Figure 10-14: Solar arrays deployment sequence (one side)

- During driving, the panels should be at fully deployed position (positioned against hard end stop). Too high dynamic loads would require electromagnetic brake (high power demand).

10.3.2 Assumptions and Trade-Offs

Section 10.1.2 is applicable

10.3.3 Baseline Design

SA hinge-line utilises active and passive hinges. Each solar panel consists of one active (DC motor coupled to a planetary gear head and a harmonic drive) and one passive hinge.

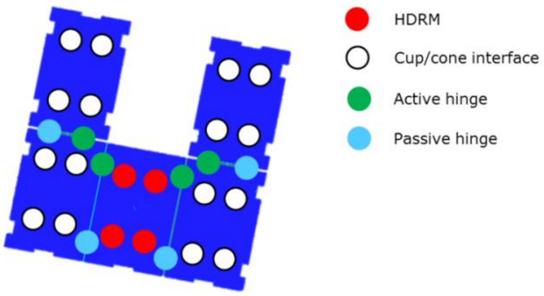


Figure 10-15: Solar Array HDRMs and deployment mechanisms

10.3.3.1 Solar Arrays HDRMs

HDRMs are based on frangibolt technology.

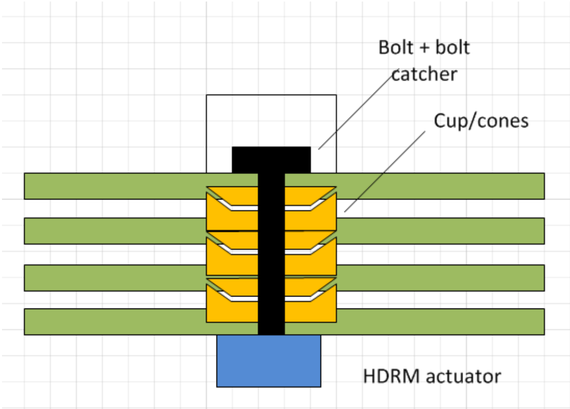


Figure 10-16: Solar Array HDRM cross-section

Based on the following calculations TiNi Frangibolt FC3 has been chosen for the described HDRMs.

Solar array HDRM calculations		
Solar arrays total area (A)	2.30	[m^2]
Solar arrays surface-density relation (ρ)	4.40	[kg/m^2]
QS loads	40.00	[g]
Total mass of the deployed solar arrays: m=ρ*A	10.12	[kg]
Number of HDRM points used (n)	4.00	[]
Force acting on the single HDRM mechanism during descent and landing	2978.32	[N]

Table 10-6: Solar arrays HDRM calculations

10.3.3.2 Solar Arrays Deployment Mechanism

The active hinge mechanism reference design concept incorporates a brushed Maxon DCX 22L motor (Figure 10-17) coupled in-line to a planetary gear head and size 17 HFUC harmonic drive. The harmonic drive output connects to a hollow shaft supported by a pair self-lubricated journal bearings to provide a high load capability within a confined space.

The following table presents the calculations of the deployment mechanism.

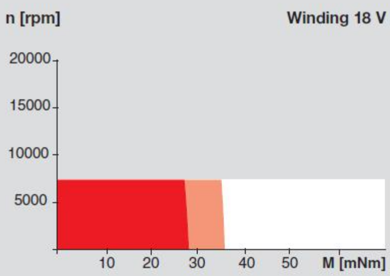
Solar array deployment calculations		
Solar panel length (d1)	0.91	[m]
Solar panel width (d2)	0.60	[m]
Solar panel thickness (d3)	0.01	[m]
Total mass of the deployed solar arrays (mt)	10.12	[kg]
Mass of the solar arrays deployed in steps 1 & 3 (m1)	5.06	[kg]
Mass of the solar arrays deployed in step 2 (m2)	2.53	[kg]
Time interval necessary to execute each 90[deg] step (t)	30.00	[s]
Mars g	3.80	[kg*m/s^2]
ExoMars Tailoring - Motorization Factor (MF)	3.00	[]
ExoMars Tailoring - Inertial Load Factor (Ki)	1.10	[]
ExoMars Tailoring - Functional Load Uncertainty Factor (Kl)	3.00	[]
ExoMars Tailoring - Frictional Resistance Uncertainty Factor (Kr)	3.00	[]
ExoMars Tailoring - Gear Resistance Losses Uncertainty Factor (Kg)	1.50	[]
Overall efficiency of the complete gear chain in ambient temperature (n) – requires preheating	0.40	[]
Planetary-harmonic gear ratio - input speed / output speed – assumed ratio 120 for harmonic drive and 40 for planetary gear (i)	4800.00	[]
Internal resistive loss in the gear stages (Tg): Tg=((1+Kg((1/n)-1))/i)	0.0004167	[]
Functional load related torque necessary to execute step 1 by 90[deg]: Tl1=m1*d2/2*g	5.768	[Nm]
Functional load related torque necessary to execute step 2 by 180[deg]: Tl2=m2*d1/2*g	4.374	[Nm]
Functional load related torque necessary to execute step 3 by 90[deg]: Tl3=m1*d2/2*g	5.768	[Nm]
Frictional resistance torque assumed for a single hinge (applied to all steps) (Tr)	1	[Nm]
Inertial torque assumed (applied to all steps) (Ti)	0.1	[Nm]
Min torque necessary to execute step 1 by 90[deg]: T1min=MF*(Ti*Ki+Tr*Kr+Tl1*Kl)*Tg	29.3	[mNm]
Min torque necessary to execute step 2 by 180[deg]: T2min=MF*(Ti*Ki+Tr*Kr+Tl2*Kl)*Tg	24.0	[mNm]
Min torque necessary to execute step 3 by 90[deg]: T3min=MF*(Ti*Ki+Tr*Kr+Tl3*Kl)*Tg	29.3	[mNm]

Table 10-7: Solar array deployment mechanisms

DCX 22 L brushed DC motor Ø22 mm

Configurable

Key Data		Precious Metal Brushes
Typical Speed/torque gradient	rpm/mNm	34
Max. nominal torque	mNm	29.8
Max. permissible speed	rpm	7160
Max. continuous output power/assigned power rating	W	20/11
Max. efficiency	%	90
Ambient temperature	°C	-30 … 85
Mech. time constant	ms	3.17
Therm. time constant winding	s	22.0
Rotor inertia	gcm²	9.01
Max. axial loading (dynamic)	N	Ball bearings: 2.5/Sinterlager: 0.1
Max. radial loading, 5 mm from flange	N	Ball bearings: 16/Sinterlager: 3
Typical noise level	dBA	52
Weight	g	90

Operating Range	Precious Metal Brushes
Continuous operation Continuous operation with reduced thermal resistance Rth_2 50% Intermittent operation	

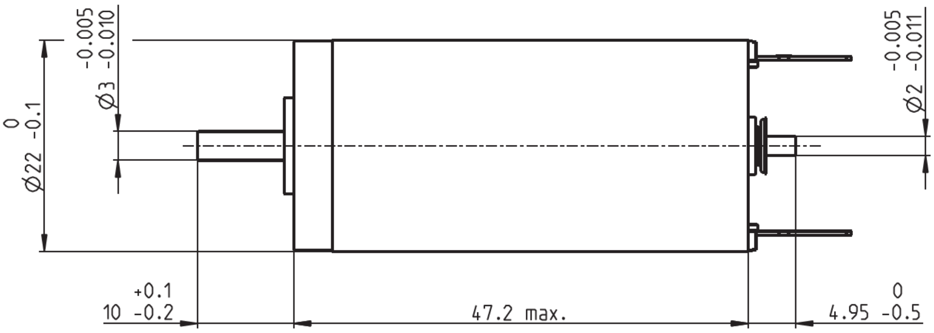


Figure 10-17: Maxon DCX 22 L motor

10.4 Robotic Arm Mechanisms

10.4.1 Requirements and Design Drivers

Section 10.1.1 is applicable. Additionally:

- HDRM/locking devices should allow to lock/unlock the robotic arm when necessary (should be locked during launch and traversing whereas unlocked during robotic arm operations)
- ATR device (Attenuated Total Reflection Spectrometer) should be accommodated in corer.

- Corer/grinder device should be able to grind the surface layer and then core into the soft soil/sediments for about 100 [mm] in order to use ATR (its window has to be in contact with the soil sample).

10.4.2 Assumptions and Trade-Offs

Section 10.1.2 is applicable.

10.4.3 Baseline Design

10.4.3.1 Robotic Arm HDRMs

HDRM mechanisms for the robotic arm were based on the design from SFR study. It was proposed to implement 3 HDRMs for the robotic arm – two holding the robotic arm limbs and one holding the robotic arm effector (corer/grinder, refer to paragraph 10.4.3.2). Each lock can be operated several times, allowing to lock/unlock the robotic arm as required.

Launch lock is implemented as a pin puller engaging a hook protruding from selected flanges along the robotic arm. It uses a DC brushless motor engaged with an externally threaded pin, as shown in Figure 10-18. When the motor is activated, the nut rotates together with the output shaft of the reducer and pulls also the threaded pin to rotate. The thread between the external case and the pin makes the pin translate itself and lock into the hook protruding from the robotic arm flange.

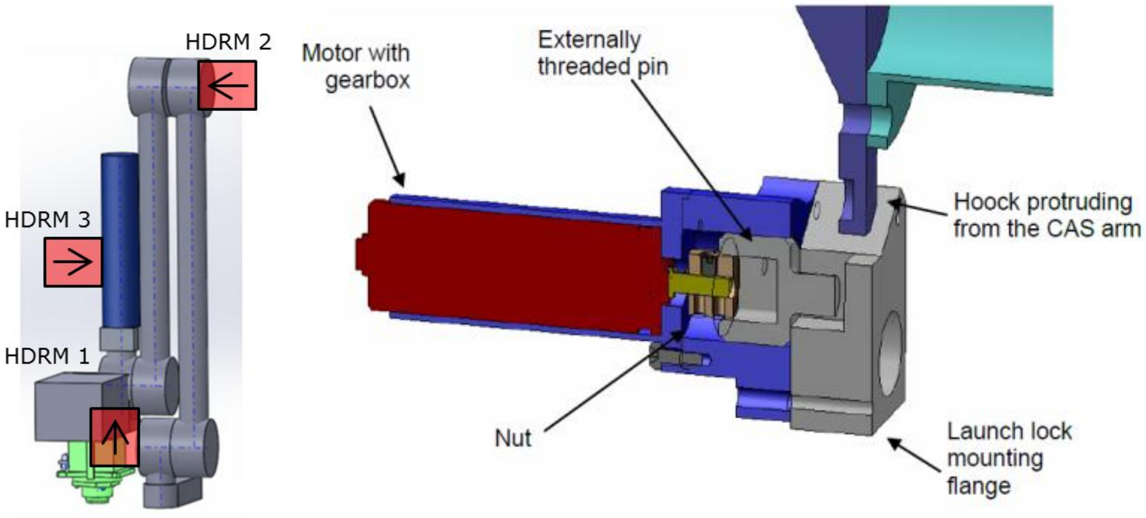


Figure 10-18: Robotic arm HDRM (CAS arm = robotic arm in case of MarsFAST)

Robotic arm HDRMs calculations		
Robotic arm's mass (m)	3.00	[kg]
QS loads	40	[g]
Number of HDRM points used (n)	3.00	[]
Forces acting on a single HDRM mechanism during descent and landing	920.26	[N]

Table 10-8: Robotic arm HDRMs calculations

The calculated forces are low, therefore this low duty joint HDRM will be able to sustain the loads acting on pin (i.e. Ø4 mm) during launch and traverse conditions.

10.4.3.2 Corer / Grinder Device

The corer device consists of a state-of-the-art coring device with the ATR device accommodated inside of the corer envelope.

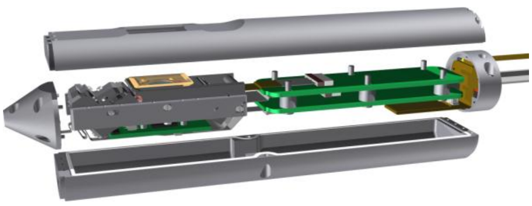


Figure 10-19: Attenuated Total Reflection Spectrometer (ATR)

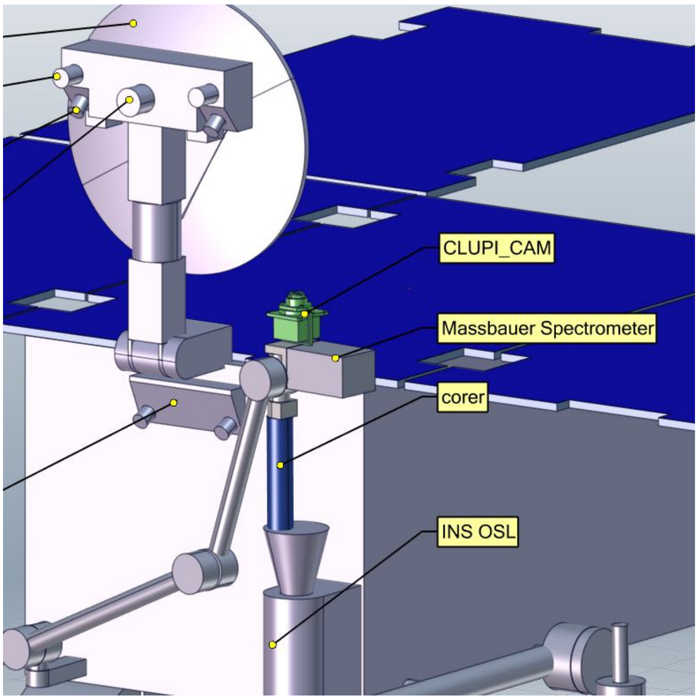


Figure 10-20: Corer/grinder mounted on the rover robotic arm

Figure 10-21 presents the proposed design of the corer device. Blades or drill-like tip of the gripper are used to grind the surface layer. The corer has an ability to drill about 100 [mm] into the soil. A window on the side of threaded corer will allow the examination of the soil with the ATR device. During the last stage of coring, gripper's spherical closing will open in order to take the sample and then to release it into the funnel mounted on top of the OSL insstrument.

The corer device is actuated by a DC brushless motor. Rotational motion is transmitted through the gearbox. There are two possible options regarding location of the motor:

- On the top of the device (resulting in increased length of the corer)
- On the side of the device (resulting in decreased length of the corer and increased complexity of the design; rotational motion is transmitted to the drill through the system of spur/bevel gears – depending on the final position of the motor)

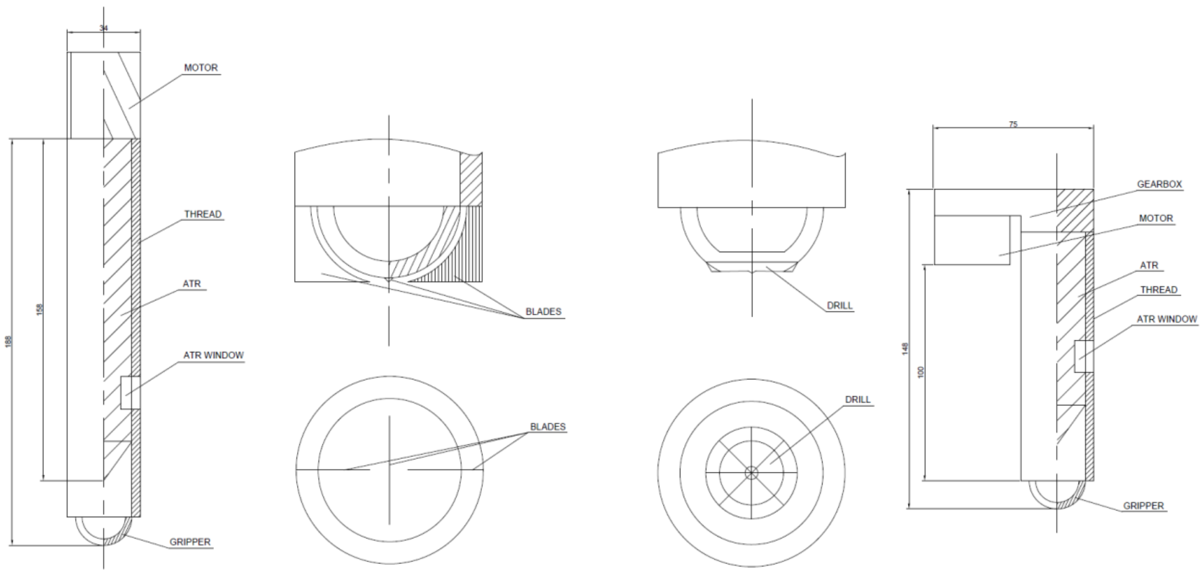


Figure 10-21: Coring/grinding device – baseline design

The second option involves a corer/grinder similar to the one used in MarsREX where the corer/grinder from Exomars pre-development activity was selected.RD[9], (Figure 10-21).

Figure 10-22: Picture Removed from this version

60 W power demand was assumed for the device. Based on the following calculations feed force and torque were estimated.

Corer/grinder feed force and torque calculations		
Corer diameter (Dc)	0.04	[m]
Cutting speed (vc)	0.05	[m/min]
Speed (n)	50.00	[RPM]
Feed per revolution: f=vc/n*1000	1.0	[mm]
Safety factor (k)	2.0	[]
Specific cutting force (kc)	350.0	[N]
Feed force: Ff=0.63*f*Dc*kc/2*k	0.0077	[N]
Power required - assumed (Pc)	0.06	[kW]
Torque: T=Pc*9500/n	11.4	[Nm]

Table 10-9: Corer calculations

10.5 Egress System

10.5.1 Requirements and Design Drivers

The following main functional requirements have been adopted:

- The egress system shall enable the rover to egress from the pallet
- The egress system shall allow the rover to egress from at least two different directions.

- Rover + egress system stowed volume shall respect the envelope 1400 x 550 x 950 mm (excluding cut outs as per Figure 10-23 on both sides of the volume allocated to ESA)

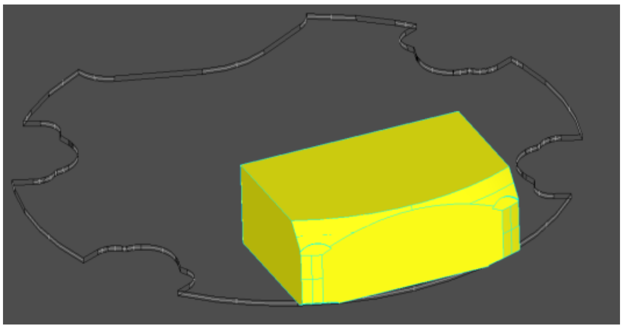


Figure 10-23: Available envelope for the rover and egress

- Maximum step height from the pallet to the ground is 400mm
- Maximum angle of the pallet with respect to the gravity vector is 20 degrees
- Maximum angle of the rails on which the rover is able to safely egress shall be 30 degrees.

The required length of the rails is calculated from the maximum step height and max. egress angle:

Rail length calculation			
Step height	h	0.4	[m]
Max angle	alpha	30	[deg]
Rail length	rail length=h/sin(alpha)	**0.8**	[m]

Table 10-10: Required rail length calculation

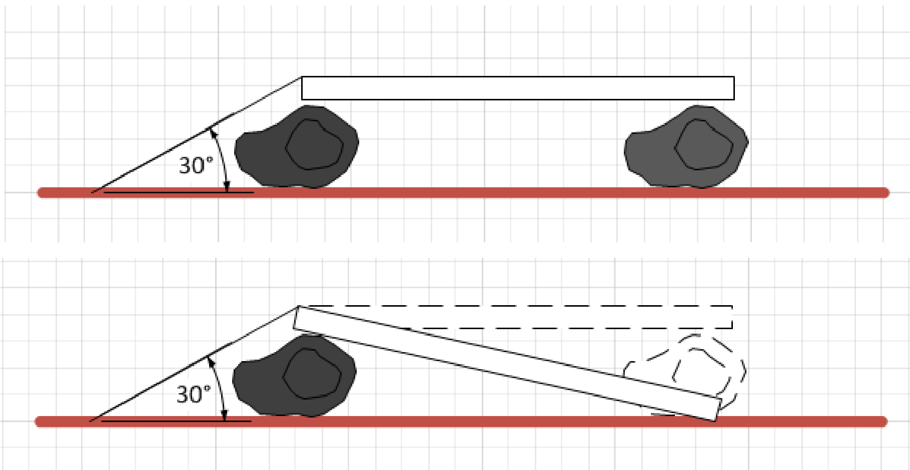


Figure 10-24: Egress-able positions of pallet

In case the combination of the requirements leads to situation as shown on Figure 10-25 the egress system cannot comply with the 30 degrees requirement unless the rails are longer than 2159 mm. Rails of such length cannot be stowed within the pre-allocated volume.

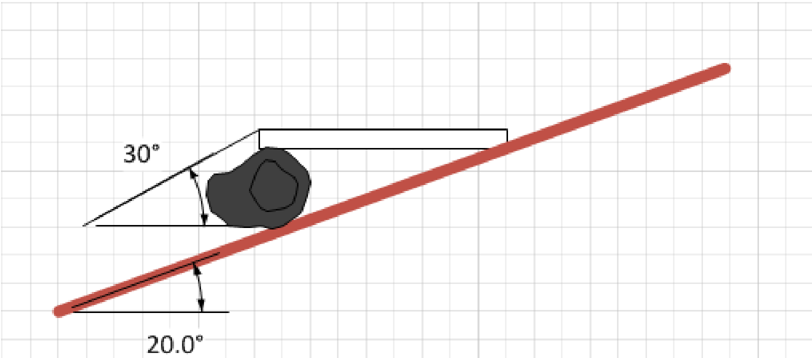


Figure 10-25: Sloped terrain and pallet on boulder

Should such situation occur, the rover must egress towards the opposite direction of the terrain slope. This means that the egress system shall allow deployment also in the direction towards a sloped terrain.

10.5.2 Assumptions and Trade-Offs

Heritage designs

Typical egress systems used in previous missions:

- Folded rails (Lunokhod, Yutu rover on the Moon)
- Folded panels with fabric slides (Mars Exploration Rover)

In various studies other systems were considered:

- Inflatable rails
- Roll-able rails
- Crane system

The second group of systems was discarded due to low TRL and more complex design and not necessarily mass/volume efficient systems. Folded panels with fabric slides cannot be accommodated in the available space.

Trade-off

Egress based on folded panels would be most simple in terms of deployment sequence. The panels design became unfeasible due to the cut-outs which are present in the allocated volume.

The following design options were considered for evaluation:

- Foldable rails – stowed vertically
- Extendable slides – stowed under the rover.

The main driver for the design has eventually become the allocated volume and the cut outs in thereof. The rails have to bridge the cut-outs in order to enable the rover to drive over them.

Concept	Foldable rails-stowed	Extendable rails-stowed

	vertically	under the rover
Maximum possible length	3	5
Heritage	5	0
Power need	5 (Spring deployment)	3 (motorized system)
Design complexity	5	1 (sliding interfaces used)
Mass	4	2
Deployment in presence of an obstacle	3	5 (rails would extend only up to the closest obstacle)
Sum	**25**	**16**

Table 10-11: Design trade-off, marking: 5-high, 1-low

Extendable rails offer longest possible egress system which would increase the probability of successful egress should the platform land on a slope and a boulder. The rails option was eventually discarded mainly due to the complexity of the design together with the need to accommodate the system under the rover (proven not feasible).

The based on the trade-off as per Table 10-11, foldable rails system was therefore selected.

10.5.3 Baseline Design

10.5.3.1 Sizing of egress rails

The rails are sized to support the mass of the rover. It is assumed that the rover mass is equally spread on its 6 wheels. Should the platform be inclined sideways (max. 20°) the weight will be distributed between the slides in the ratio 2:1.

Forces on rails			
Mass rover	Mrov	150. 0	kg
gMars	g	3.71	m/s2
Wheel distance	Lw	0.53	m
Total weight	W=Mrov*g	556.5	N
Wheel load	L=W/6	92.75	N
side load factor	s	2	
Wheel w-c load	Lwc=L*s	185.5	N
Flight limit load	Lfl=Lwc*1.25	231.86	N
Design load	Ld=Lfl*1.25	289.85	N

Table 10-12: Forces on rails

The rails can be made of CFRP sandwich panels with aluminium honeycomb core. The driver for the panels sizing will be stiffness and strength of attachment points rather than strength vs. bending moments from the egressing rover.

Low stiffness panels will cause dynamic response to the loads from egressing rover. Rather stiff panels were therefore selected which result in max bending deflection < 3.5 mm.

The selected sandwich panel is M55 CFRP ([[0,60,-60]s]s with & 3/16-5056-.0007 Honeycomb core.

SANDWICH PANEL DESIGN

Density of laminate	1654	kg/m^3	Facesheet	[[0,60,-60]s]s		
Facesheet thickness	1.50	mm	Core material	3/16-5056-.0007		
Bonding	0.35	kg/m^2				
Density of core	32.04	kg/m^3				
Core depth	10	mm				
Bending inertia	75	mm^4		Total panel thickness	13	mm
Panel area density	5.63	kg/m^2				
Panel equivalent density	433.26	kg/m^3	(required for CAD applications)			

Figure 10-26: Sandwich panel configuration

Bending and strength has been verified and the results are presented in Table 10-12. Since the wheel distance is slightly higher than half of the length of the rail a simply supported beam with load in the middle has been used to model the load case.

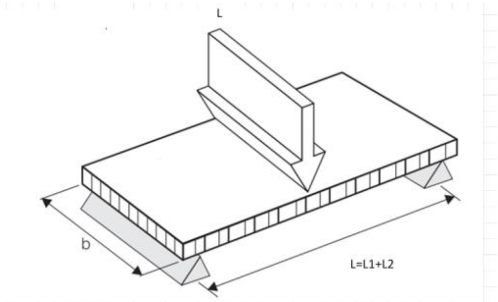


Figure 10-27: Load introduction into the panel

Calculation has been done according to the panel manufacturers guidelines (available at RD[19]). Both the facesheet and core stresses are well within material allowables.

10.5.3.2 Panels masses

According to the selected sandwich panel type the masses have been calculated. Ramps which unfold directly are composed of two panels 1. Ramps which shall be erected before unfolding compose of two panels 1 and an additional panel 2.

Egress panels sizes		
	length [m]	width [m]
panel 1	0.55	0.14
panel 2	0.14	0.19
area density	5.63	kg/m2
mass panel 1	0.43	kg
mass panel 2	0.15	kg

Table 10-13: Sandwich panels masses per panel

The complete panel masses shall include the masses of interface structures for connecting the hinges, HDRMs and side rails.

Egress panels masses		
mass panel 1	0.7	kg
mass panel 2	0.2	kg

Table 10-14: Complete panel masses per panel

10.5.3.3 Hold down and release

The egress panels need to be held down during the launch and then sequentially released. HDRM mechanisms from NEA Electronics were selected for this function. They offer a range of preloads and very low release shock. Also the energy consumption is very low.

The sizing is driven by the launch dynamic loads. The assumption is that the panels will proabaly respond to the launch acoustic environment. Therefore 50g quasistatic load was assumed which is higher than the descent and landing loads The HDRM itself can only provide axial preload and counteract forces but the bending moments must be counteracted by additional cup/cone interfaces.

The complete HDRM assembly is composed of one or several cup cones which take the bending and shear loads and the HDRM itself provides the preload against the loads combination.

The number of the HDRM points is determined by the opening sequence. It is clear that the sequence shall be such that:

a. The rover is not jeopardised by the deployment
b. The rails can be deployed in presence of an obstacle

This requires that the deployment of the panels is performed sequentially. As a consequence multiple HDRM points must be used.

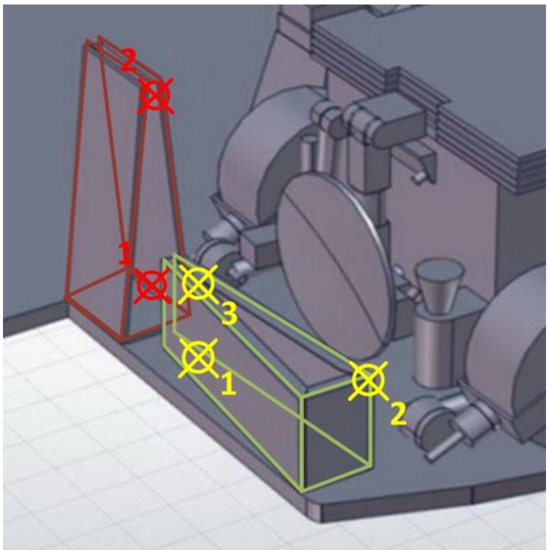


Figure 10-28: HDRM positions

A possible location of hold down points and their firing sequence is shown in Figure 10-28.

In the case of the rails which are stowed standing up (depicted in red) only 2 HDRMs are theoretically required. The first one is required to hold the structure during the launch and landing. The second HDRM function is to deploy the second panel only after both panels have moved away from the rover.

The sizing case is obviously HDRM number 1. For the HDRM number two the smallest NEA HDRM will be sufficient.

HDRM preload calculation		
HDRM cup/ cone half angle	6.00E+01	degrees
mass	2.16E+00	kg
acceleration in x	5.00E+01	g
acceleration in y	5.00E+01	g
acceleration in z	5.00E+01	g
g	9.81E+00	m/s2
Fx	1.06E+03	N
Fy	1.06E+03	N
Fz	1.06E+03	N
CoG position	2.75E-01	m
Tz	2.91E+02	Nm
Width	6.00E-02	m

HDRM preload calculation		
Fp to react Tz	4.86E+03	N
Tx	2.91E+02	N
Depth	1.90E-01	m
Fp to react Tz	1.53E+03	N
Total required preload	1.00E+04	N
Fp= Fy+Fpz+Fpz+ tan(60)*sqrt(Fx^2+Fz^2)		

Table 10-15: HDRM preload calculations

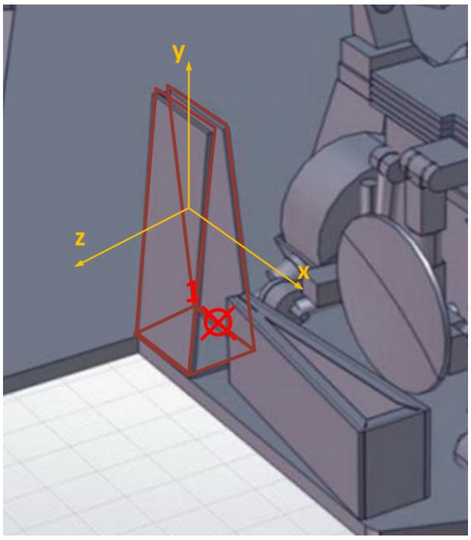


Figure 10-29: Coordinate system assumed for the calculations in Table 10-15

The required preload is 10 kN. NEA 9102G which is rated for 17.8 kN preload was selected.

For the other configuration of the stowed panels (depicted in yellow on Figure 10-28) an additional HDRM is required to keep the structure stiff. The deployment sequence again follows the HDRM numbering.

Should the detailed structural analysis show any problems with high stresses in the panel hinges or their attachment points, a possible solution is to include additional structure to introduce more stiffening in the folded panels stack. The alternative design is shown on Figure 10-30 to Figure 10-32. The supporting structure and the HDRM points are shown in grey and red respectively. The supporting structure would also incorporate three additional cup/cones interfaces which counteract the bending moments around x and y axes.

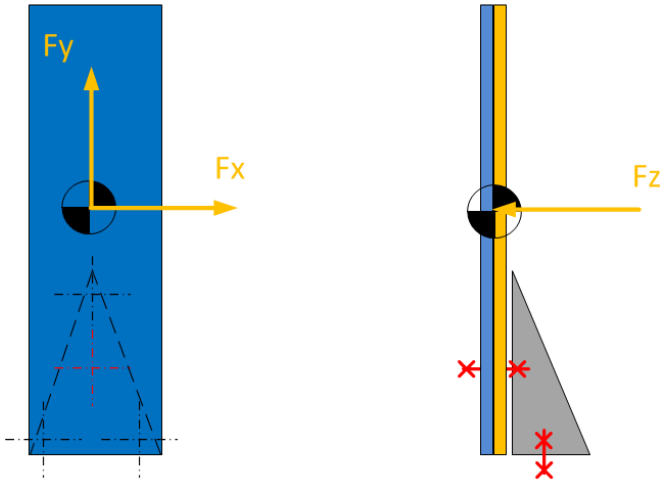


Figure 10-30: Alternative way off stowing the rails with support structure

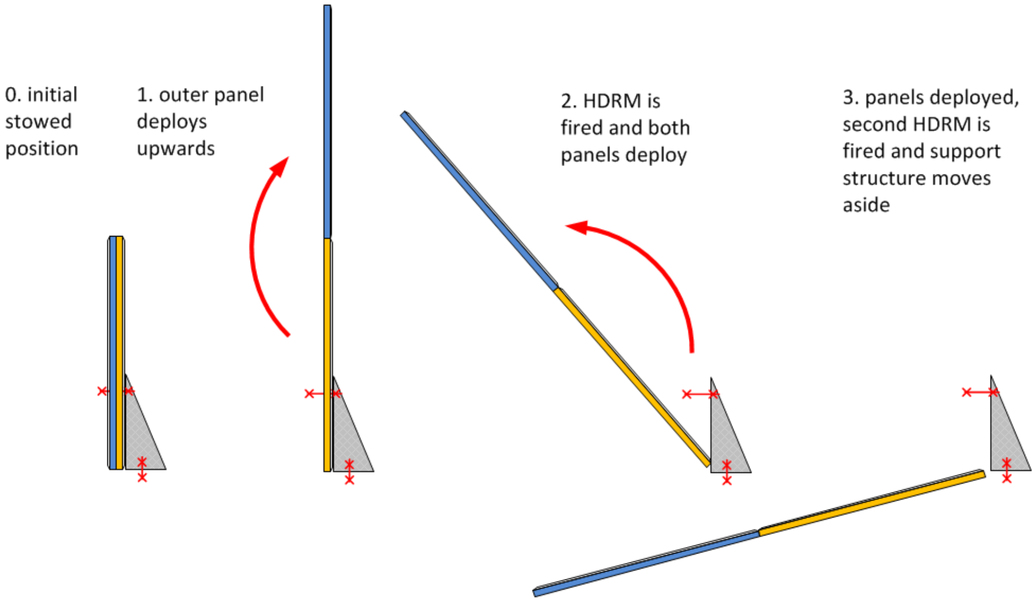


Figure 10-31: Alternative way off stowing the rails – side view of deployment sequence

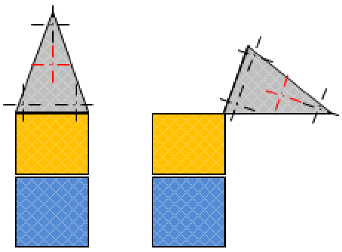


Figure 10-32: Alternative way off stowing the rails – front view of deployment sequence (steps 2 & 3 only)

The drawback of this solution is that the structure must be removed from the path of the egressing rover. Nevertheless this configuration has been assumed for the mass budget and the masses of the structure and additional HDRMs were included.

The actual deployment of the panels is done by spring actuated hinges. The torque to actuate the hinges shall overcome the mass of the panels and the resistive torques in hinges. The resistive torques of the hinges will possibly be increased by a sealing system which should prevent any dust or sand accumulating in the journal bearings. Therefore a resistive torque of 2 Nm has been assumed per hinge line. Normally a torque order of magnitude lower would be expected.

Required deployment torque		
Deployed panels mass	2.2	kg
Cog position	0.3	m
Mars g	3.7	m/s2
Tg from gravity	2.2	Nm
Tr resistive torque	2.0	Nm
Required actuation torque	1.76E+01	Nm

Table 10-16: Deployment torque calculations

Such torque can be provided by a coil spring. Tape springs (as shown on Figure 10-33) could be interesting design alternative offering less complicated design than standard spring actuated hinges. Quite possibly tape springs could be used alone without additional hinges as they offer also dimensional stability when deployed to certain extent.

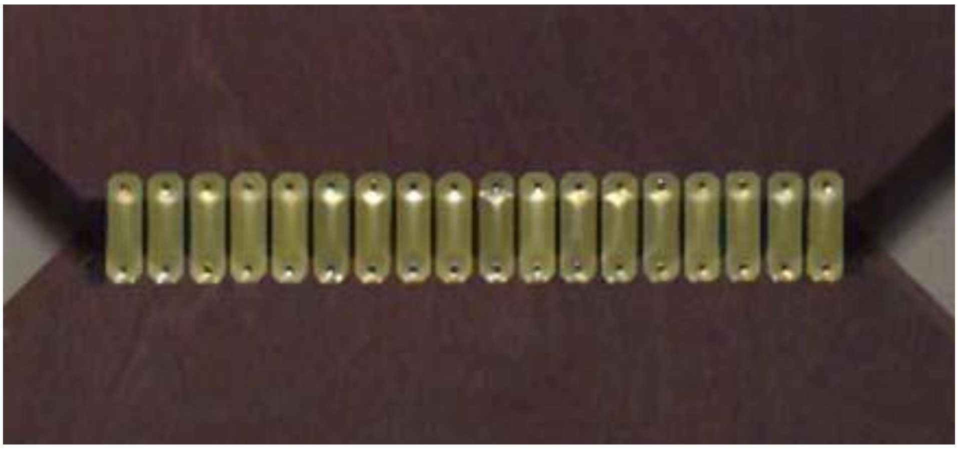


Figure 10-33: panels joined with tape springs

10.5.4 Safety Features

The rover egress shall be performed in a controlled way. Therefore any sliding of the rover while egressing the ramp shall be excluded by design. In the present design side sliding is prohibited by the rims of the rails.

Sliding on the rails can be also avoided by protrusions on the rail surface.

Friction coefficient can be also increased by appropriate materials combination, coating or controlling the surface roughness on the macro and micro scale.

10.5.4.1 Deployment

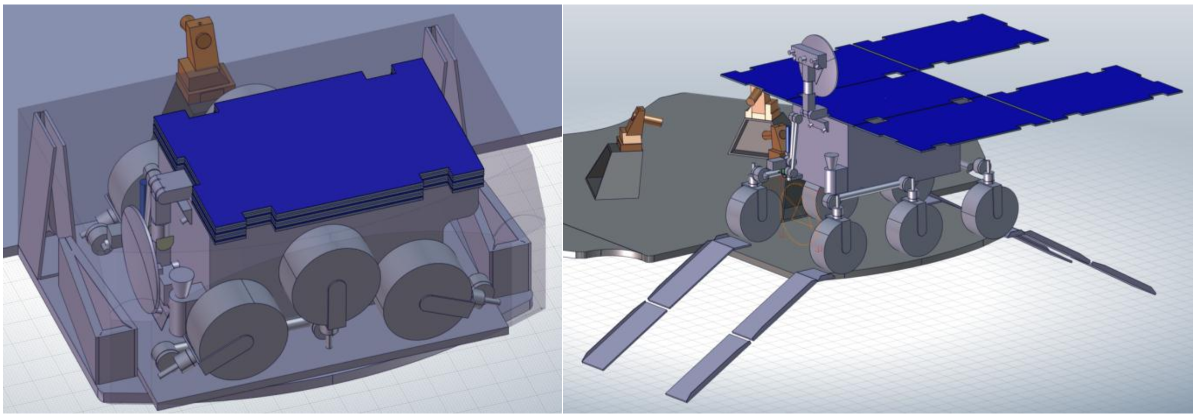


Figure 10-34: Egress system stowed and deployed

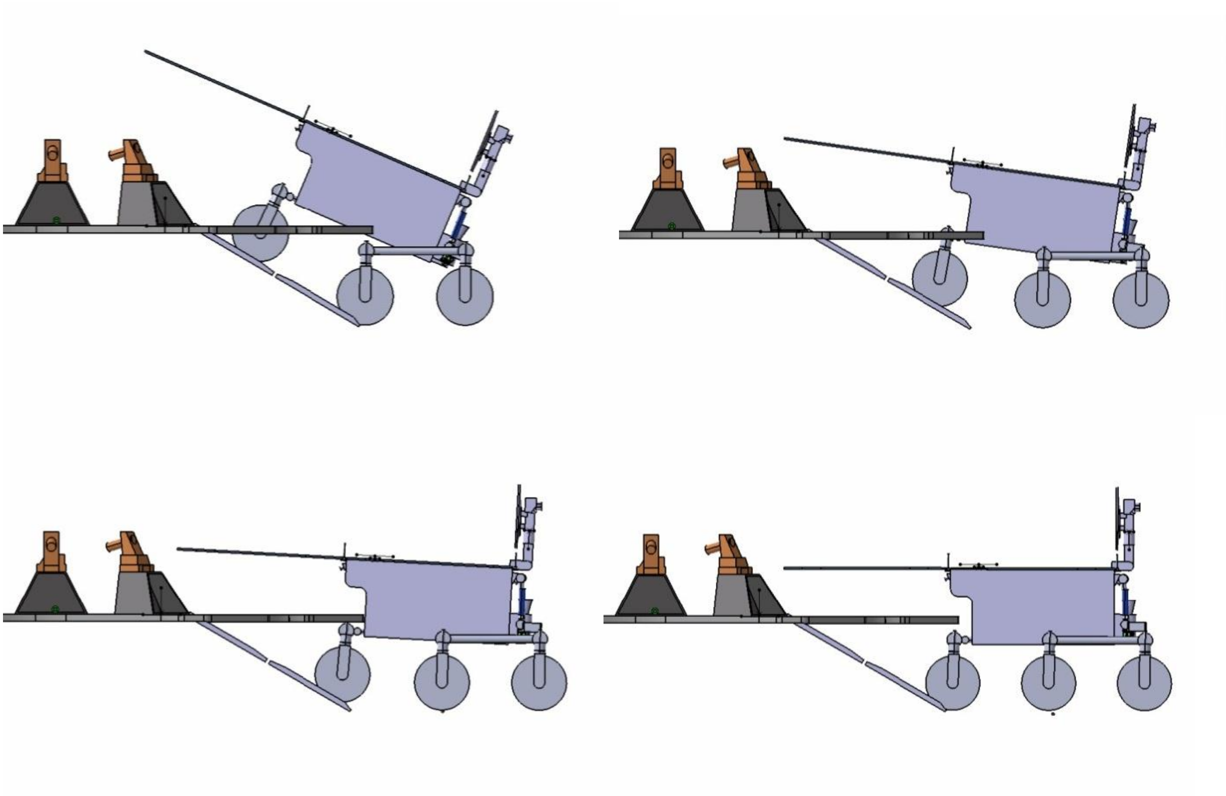


Figure 10-35: Rover egress

10.6 List of Equipment

10.6.1 Mass of the Units

Element 1	Rover			MASS [kg]			
Unit	Unit Name Click on button above to **insert new unit**	Part of custom subsystem	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
1	HDRM rover (platform)		4	0.3	To be developed	20	1.4
2	HDRM rover (wheels)		6	0.2	To be developed	20	1.1
3	Umbilical release mechanism		3	0.1	To be modified	10	0.2
4	HDRM camera head (mast)		1	0.3	To be modified	10	0.3
5	Mast Deployment mechanism (tilt actuator)		1	0.5	Fully developed	5	0.5
6	HDRM (solar array, 4 panels)		4	0.1	To be modified	10	0.4
7	Deployment (solar array, 4 panels)		4	0.3	To be modified	10	1.3
8	Hinges (solar array, 2 panels)		4	0.3	To be modified	10	1.3
9	HDRM HGA		3	0.3	To be developed	20	0.9
10	Mast Deployment mechanism (pan actuator)		1	0.5	Fully developed	5	0.5
11	Corer/grinder (incl. ATR)		1	0.7	To be developed	20	0.8
12	HDRM Robotic Arm		3	0.1	To be developed	20	0.3
-	Click on button below to insert new unit						
SUBSYSTEM TOTAL			12	7.9		14.2	9.0

Table 10-17: Rover Mechanisms subsystem (mass of the units)

Element 2	Egress System				MASS [kg]			
Unit	Unit Name Click on button above to insert new unit	Part of custom subsystem	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
1	Panel (size #1)		8	0.7	To be developed	20	6.7
2	Panel (size #2)		4	0.2	To be developed	20	1.0
3	Hinge (type #1)		4	0.8	To be modified	10	3.5
4	Hinge (type #2)		4	0.4	To be modified	10	1.8
5	Hinge (type #3)		2	0.4	To be modified	10	0.9
6	HDRM (support structure #1)		2	0.6	To be developed	20	1.4
7	HDRM (support structure #2)		2	0.8	To be developed	20	1.9
8	HDRM (NEA 9100)		14	0.1	Fully developed	5	1.0
-	Click on button below to insert new unit						
	SUBSYSTEM TOTAL		8	15.8		15.5	18.2

Table 10-18: Egress subsystem (mass of the units)

10.7 Options

10.7.1 Solar Arrays Deployment Mechanisms based on Passive Hinges

An alternative option to be considered involved design of the solar array deployment mechanisms is based on the tape springs. Each solar panel is composed of two hinges one of them actuated by a spring.

Advantages:

- Lower energy demand
- Simpler design of the deployment mechanism.

Disadvantages:

- Additional HDRMs required to accomplish sequential deployment
- No tilting of solar panels.

10.8 Technology Requirements

The following technologies are required or would be beneficial to this domain:

Included in this table are:

- Technologies to be (further) developed
- Technologies available within European non-space sector(s)
- Technologies identified as coming from outside ESA member states.

Equipment and Text Reference	Technology	Suppliers and TRL Level	Additional Information
HDRM	Burn wire preloading concept	TRL 9 NEA Electronics	Not European source, similar mechanism is being developed by RUAG Vienna.
HDRM	Frangibolt technology based on shape memory alloys	TRL 9 Tini aerospace	Not European source, similar mechanism is being developed by Arquimea company in Spain.
HGA	Geared	TRL 9 from MER	Technology available from

Equipment and Text Reference	Technology	Suppliers and TRL Level	Additional Information
actuators	actuators	mission	European suppliers. Project development would be required.

11 ROBOTICS

11.1 Locomotion Subsystem

The locomotion subsystem gives the rover the ability to move over a terrain. This chapter describes the wheels, joints, motors and main mechanisms of the subsystem and how these components are connected to the rover body.

11.1.1 Requirements

The locomotion subsystem shall give the rover the ability to traverse 20km in a straight line over a timespan of 110 sols. This should be accomplished in a reliable and fast way on one hand but on the other hand the locomotion subsystem has to be very compact during the transfer to Mars. Therefore, providing the locomotion system with two modes, a stowed and a deployed mode, becomes a requirement.

To fulfil the fast mobility requirement the rover should be able to drive over obstacles in order to shorten its ground track. This is the main driver to size the wheel as big as possible.

SubSystem requirements		
Req. ID	**STATEMENT**	**Parent ID**
LOC-010	The Rover shall be able to overcome obstacles of 20 cm in height.	
LOC-020	The Rover shall have a ground clearance of at least 30 cm.	
LOC-030	The Rover shall have a nominal speed greater or equal to 1.8 cm/s at a flat terrain.	
LOC-040	The Rover shall be able to traverse a 20° slope uphill on loose underground.	
LOC-050	The Rover shall be able to deploy on the landing platform by itself.	
LOC-060	The Rover shall remain stationary stable up to more than 35° inclination in respect to gravity.	
LOC-070	The locomotion subsystem shall have two configurations: a stowed and a deployed mode.	

11.1.2 Assumptions and Trade-Offs

A trade off between different possible locomotion systems is made. Several systems from the past were reviewed. The MarsREX CDF RD[9] locomotion system trade-off fits perfectly within the MarsFAST study and is used to make the trade off between the different locomotion principles (6×6×6, 6×6×4, …). This document provides a good understanding of this trade-off process. This mission will use the triple bogie system as baseline which is able to keep the rover body almost at a horizontal position when some wheels are driving over a rock. The main drivers for this choice are:

- 6 wheels have a significantly better obstacle negotiation ability than 4 wheels
- A 3-Bogie Locomotion System as used for the ExoMars rover (i.e. 'concept E' RD[25] without the original parallel linkages) has design heritage in ESA RD[26] and is accepted in the community to have the best *(traversability + gradability) / mass* ratio, although the tractive performances are still to be tested and characterized on Mars-representative soil conditions.

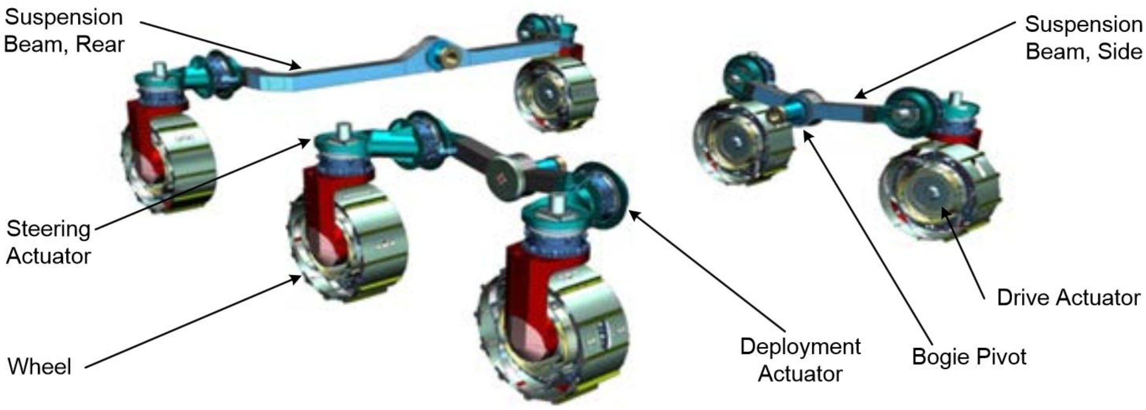


Figure 11-1: Triple bogie system

The triple bogie system is a baseline design and a deeper investigation of the locomotion system is required to fit the rover into the two different configurations.

A trade-off has also beenmade between the different deployment systems. Two solutions are deeply analysed and evaluated considering the heritage, the mass & volume constraints and the extra functionality they could provide. Rotary mechanisms for deployment systems are usually preferred over translational mechanisms. Two of the main drivers for this choice are to ease the lubrication and to prevent jamming. The way the wheels can be stowed in this compact volume, making them as big as possible within the given constraints, will be an important driver for choosing the deployment system. The extra manoeuvring capability that these mechanisms may provide is considered in the trade off as well. The two designs which are the most applicable to this mission, thus which were investigated, are a "rotating bogie system" and the "wheel walking principle". Both deployment systems have rotary actuators and provide extra manoeuvring capabilities that can be used to save the rover out of trapped situations.

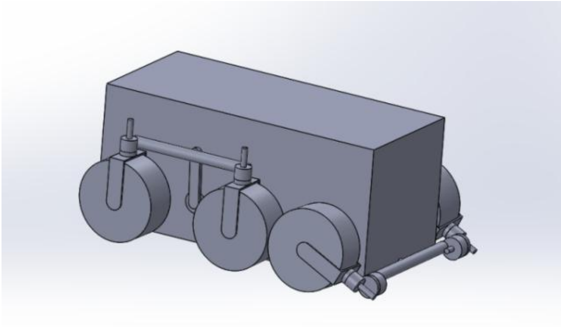
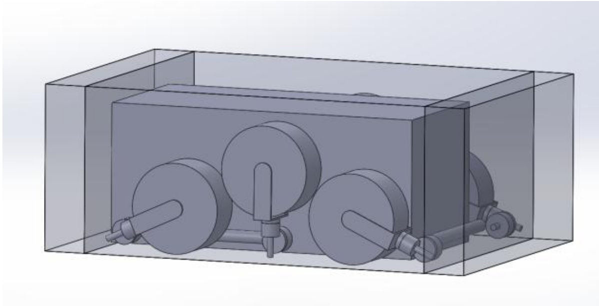
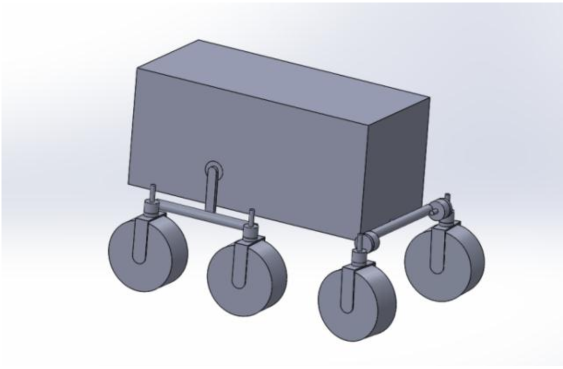
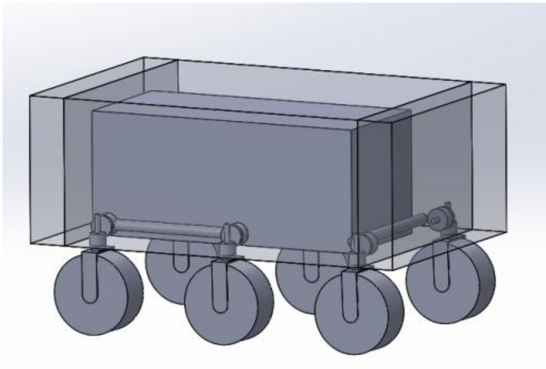
	A: Rotating bogie mechanism	B: Wheel-walking mechanism
Stowed		
Deployed		

Table 11-1 Deployment trade off

11.1.2.1 Solution A: Rotating bogie

After the actuation of the HDRMs, the rover shall start the deployment sequence by lifting itself from its belly. This is accomplished by rotating the side bogies and the rear wheels down while rotating the wheels in the opposite direction to prevent wheel slippage. The rover can begin the egress followed by its normal traverse.

Trapped situations:

When the rover is trapped in a difficult terrain, e.g. loose soil, it can start a crabbing motion by rotating the side bogies and rear wheels. This provides the rover an extra chance of getting out of this trapped situation and can be considered as a sophisticated manoeuvring capability. Although we think this system has a high potential of saving the rover and the mission it is still a new principle and it has never been tested before.

11.1.2.2 Solution B: Wheel walking principle

With this system the rover can lift its body by rotating the front and rear wheels away from the rover to make space for the middle wheels and provide them the space to touch the lander surface. As these middle wheels are touching the bottom, the six deployment motors can simultaneously start pushing the rover from its belly on its wheels. During this operation the wheels will rotate in the opposite direction with respect to the deployment motors, which helps lifting the rover body without wheel slippage. The locomotion system then acts as a normal triple bogie system.

Trapped situations:

As the rover isn't able to move or has to cross difficult terrain, this deployment or walking motors can be actuated. By moving them sequentially they can help the rover getting out of this trapped situation. Another application of this wheelwalking motor is to improve traction and stability of the rover on a soil slope or during the egress manoeuvre, by shifting the centre of gravity with respect to the places where the wheel touches the underground. During test performed by the Russian company VNIITransmash on volcanic terrain on the Kamchatka peninsula decades ago as well as during recent ESA internal lab activities at TEC-MMA), wheel-walking mechanism has been demonstrated to be very useful in loose soil. Although backdriving of walking motors while climbing rocks is still to be tested.

11.1.2.3 Conclusion

Due to the fact the wheel walking principle has already been proven in previous tests and it is applied as a deployment system on the ExoMars rover this is the preferred mechanism. This system provides the ability to choose slightly bigger wheels as well.

11.1.3 Baseline Design

11.1.3.1 Wheel

The wheel is an important part of the locomotion subsystem. During this study, the goal is literally not to "reinvent the wheel" but use wheels from previous studies and missions. The driving parameters for sizing the wheel are the obstacle traversability, the efficiency and the slope gradability. Therefore the EGP (Effective Ground Pressure) (see explanation below), is used as a comparison unit.

Traversability

In theory, the rover is able to travel over rocks or obstacles which are the size of the wheel diameter (6 wheeled platform). Following this rule it's easy to conclude that the bigger the wheel, the fewer obstacles the rover needs to avoid which will end up in shortening the path to get to final destination.

Effective Ground Pressure (EGP)

The EGP is calculated by dividing the wheel load by the product of wheel-width and wheel-radius. This is just a rough comparison measure which does not take into account the nature of the soil and the resulting sinkage, nor any wheel flexibility, nor the influence of the grousers. However it is very easy to calculate and use for relative comparisons of wheel sizes between missions. Thus, EGP is linearly proportional to the inverse of the width and the diameter of the wheel.

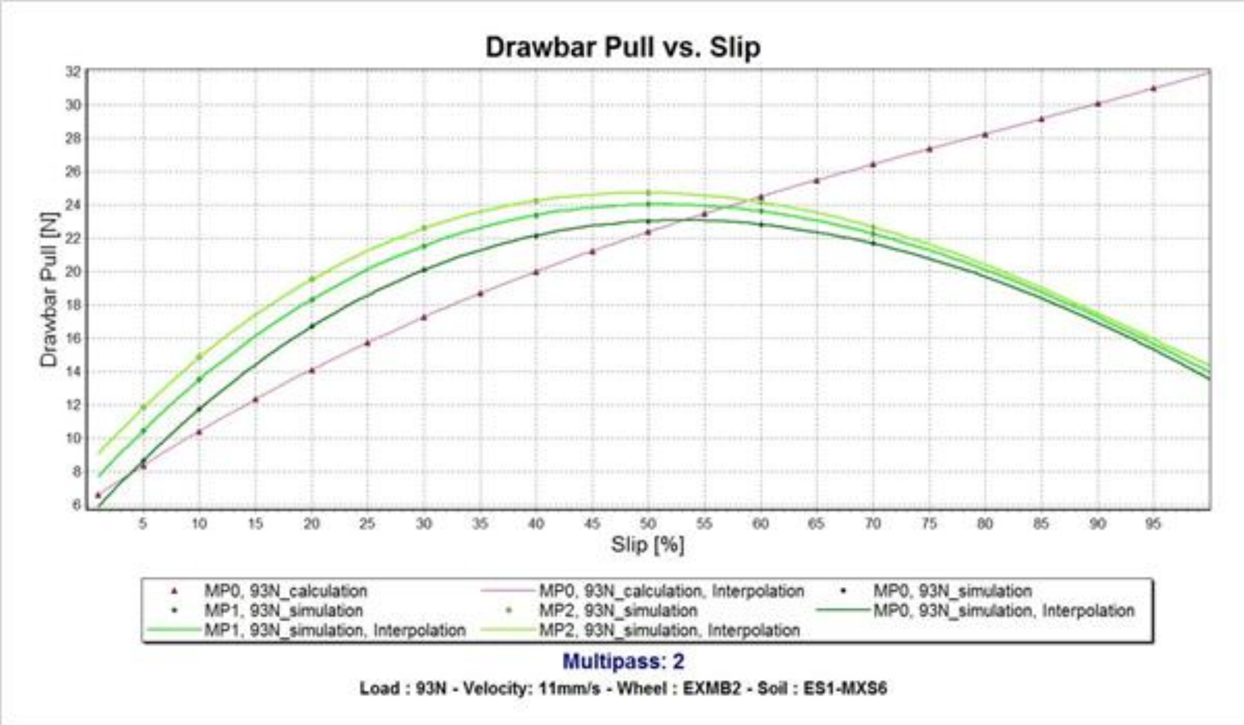


Figure 11-2: Drawbar Pull vs. Slip; red= interpolation of test data (Ø250 mm), dark green= simulation for the tested values (Ø250 mm), medium green= simulation data for Ø300 mm, bright green= simulation data for Ø 350mm

Comparison of EGP:

- SFR by Astrium EGP ≈ 4 kPa
- ExoMars Rover with flexible wheels EGP ≈ 12 kPa
- JPL's MER and MSL Rover EGP ≈ 5.7 kPa
- MarsFAST Rover EGP ≈ 4.75 kPa

Gradability

To achieve a high gradability, the "max. drawbar pull" to "wheel-load" ratio is maximised. As seen in Figure 11-2, the drawbar pull increases by increasing the wheel diameter. The same happens with an increased width. This shows that a lower EGP is increasing the gradability. The adopted MarsFAST value of ≈ 4.75 kPa is just below the MER and MSL Rover's value. Taking the theory of achieving worse gradability due to downscaling the system (Ref RD[23]) and the former stuck situation of one MER rover into account, the decision goes for a maximum wheel size in diameter and width that fits in the system allocated volume.

Conclusion

For these various reasons, the design of the wheel should be as big as possible. An optimum wheel size with a width of 13 cm and a diameter of 30 cm was achieved.

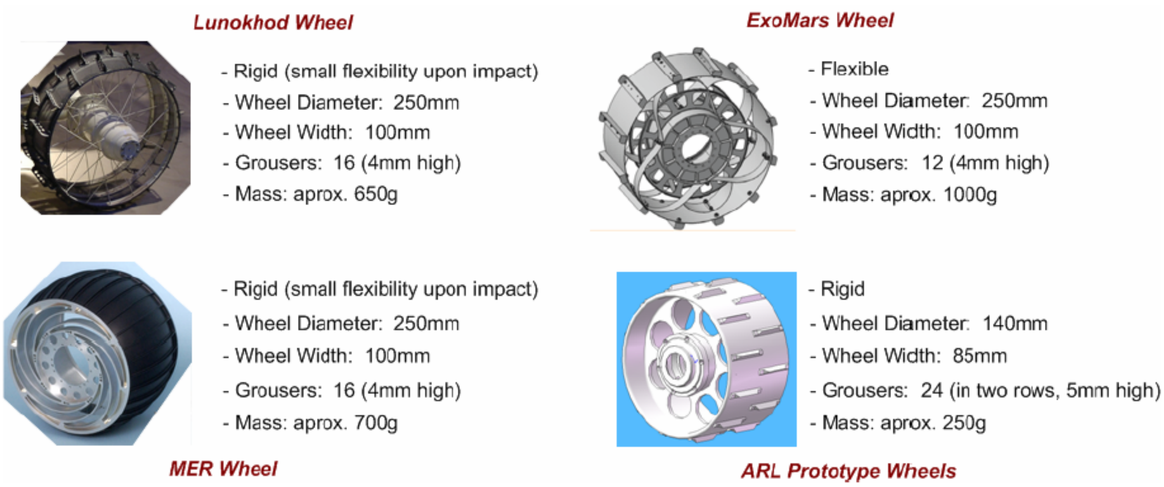


Figure 11-3: wheels from several missions and one lab prototype

The design is scaled to fit the wheel to the MarsFAST rover. The mass is linearly proportional to the wheel width and approximately proportional to the diameter to the power of 1.5, because the wheel rim length is proportional to the diameter. The following formula is used to calculate the MasFAST wheel mass.

$$\text{Mass}_{\text{MarsFAST}} = \left(\frac{\left(\frac{\text{Mass}_{\text{example}}}{\text{width}_{\text{example}}} \right) * \text{Width}_{\text{MarsFAST}}}{\text{diameter}_{\text{example}}^{1,5}} \right) * \text{Diameter}_{\text{MarsFAST}}^{1,5}$$

	Previous designs	*MarsFAST design*	
Width		**130.00**	**mm**
Diameter		**300.00**	**mm**
Lunokhod Wheel	650.00	1110.78	g
ExoMars Wheel	1000.00	1708.89	g
MER Wheel	700.00	1196.23	g
ARL Prototype Wheels	250.00	1199.37	g

Table 11-2: Wheel interpolation

The Automation and Robotics Laboratory (ARL) prototype (rigid wheel) provides a good indication but it isn't a flight model. The ExoMars Wheel is a flight design of a flexible wheel which has not been selected for MarsFAST due to its complexity and perceived vulnerability. The flexibility of this wheel in combination with the necessary bump stops directly increases the density of the wheel. The Lunokhod and the MER wheel designs (rigid wheel) are considered to be the best fit for this mission concept. These wheels provide a good estimation of the mass of the MarsFAST wheel by calculating their average. This will be 1154g per wheel.

11.1.3.2 Bogie system

Figure 11-4 shows the bogie system. The motion of the three passive joints is shown by the blue arrows. This passive joint bogie system keeps the rover body in a very stable and close to horizontal position during the traverse over an uneven terrain.

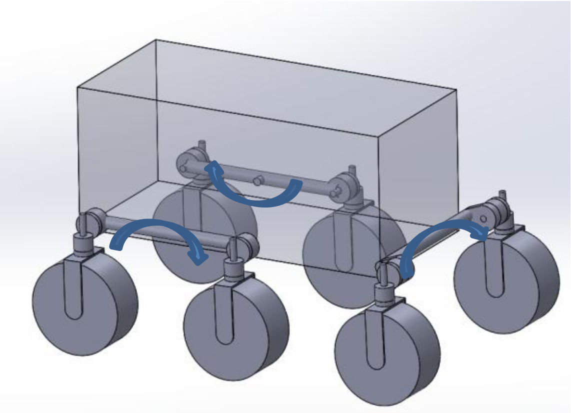


Figure 11-4: Passive boogie joints

At the end of these bogies, the legs and wheels of the rover are attached. These are all motorised joints. There is one driving motor allocated inside every wheel, one steering motor on top of the fork which holds the wheel and a deployment and walking motor is attached to the steering motor. The three motors are shown in Figure 11-5. So the total locomotion formula of the rover is 6x6x6 which includes wheel walking and crabbing (driving sideways) motions. Steering motors on the middle wheels enable the crabbing motion and add redundancy to the locomotion subsystem.

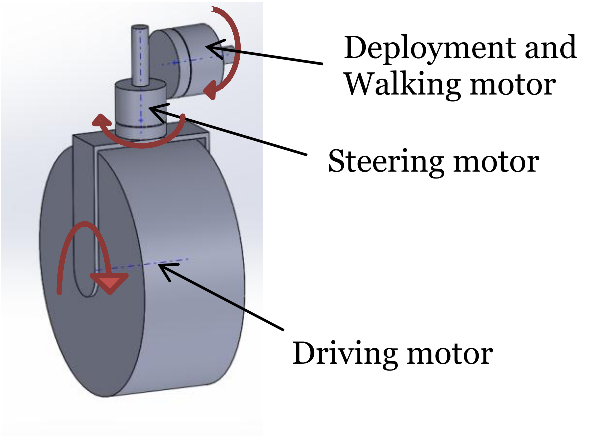


Figure 11-5: Motors and placement

11.1.3.3 Estimated Loads on Actuators

The loads for the actuators are based on the geometric configuration of:

All calculations for the given System:		
Wheel Diameter	300	[mm]
Wheel Width	130	[mm]
Number of wheels	6	

Distance axis 1 -2	200	[mm]
Distance axis 2 -3	200	[mm]
System Mass	150	[kg]
Height of centre of mass from the centre wheel axis	250	[mm]
Gravity	3.711	[m/s^2]

Table 11-3: System dimensions as baseline for load calculations

From this, the loads on the actuators in different locomotion situations can be calculated. The following assumptions are used for the layout:

Slope angle	25	plus 5° due to sinkage
nominal speed	65	[m/h] (= 1.8m/s)
rolling resistance coeff	0.12	{refers to driving}
friction coeff wheel-soil	0.6	{refers to steering}
gear efficiency of first planetary stages	0.7	{15-23 in reduction}
gear eff. of secondary stage	0.7	{100 reduction}
overall uncertainty factor of calculations	1.5	
motorization factor applied	2	

Table 11-4: System conditions as baseline for load calculations

Torque while steering a rear wheel on a slope:		
Distance rear-bogie to COM-gravity	383.5	[mm]
Distance front axis to COM-gravity	366.5	[mm]
Load on rear pair:	272.0	[N]
Load on 1 rear wheel:	136.0	[N]
T_steering_max:	5.30	[Nm]

Table 11-5: Torque estimation while steering a rear wheel on a slope

Torque while driving for a rear wheel on a slope:		
total drawbar pull:	235.1	[N]
pull from 1 rear wheel:	57.45	[N]
Torque rear wheel at slope:	8.62	[Nm]

Table 11-6: Torque estimation while driving up a slope for the rear wheel

Max Torque while driving over an obstacle:		
necessary force in vertical direction:	185.55	[N]
necessary force against an obstacle:	231.94	[N]
Torque per pushing wheel:	8.70	[Nm]

Table 11-7: Torque estimation for driving over a worst case obstacle

Torque for deployment (without active drive help):		
Distance egress axis to driving axis:	220	[mm]
T_egress_max	40.821	[Nm]

Table 11-8: Torque estimation for deployment

Table 11-4, Table 11-6, Table 11-7 and Table 11-8 provide the input data for the actuator sizing by giving the torque numbers in the worst case scenarios. The idealised model behind Table 11-7 is that the rear wheel pair and the centre wheel pair are pushing the front set against the obstacle to provide enough traction for the front wheel pair to climb the vertical parts of obstacles. The green highlighted lines show the peak loads for each actuator system and are therefore used as the baseline of the further sizing.

11.1.3.4 Sizing the motors

The motor gearbox combinations are based on currently available standard products. The selection is made by first finding a suitable secondary gear stage for the necessary resilience and then finding matching primary gearheads plus motors. Where possible, the primary gearhead plus motor package should fit inside the hollow-shaft of the secondary gear stage for reasons of compactness and thermal management.

Configuration for Deployment actuators (wheel walking):

- Secondary gear stage: HarmonicDrive AG CPL-2A-17 120
- Primary gear stage: Maxon planetary gearhead GP 16 C Ø16 mm
- Motor: Maxon RE-max 17 Ø17 mm
- System Reduction: 67320
- Estimated mass of housed actuator system:

Deploy mass assumption:		Comment
gear+motor	159	
bearing	80	
output housing	70	
motor & HD Housing	60	
Encoder	15	
interface	50	
sealing s/s	20	
SUM	**454**	[g]

Table 11-9: Mass assumption for one Deployment Actuator

Configuration for steering actuators [setup used in MarsREX study]:

- Secondary gear stage: Harmonic Drive AG CPL-2A-11 100
- Primary gear stage: Maxon planetary gearhead GP 22M Ø22 mm
- Motor: Maxon RE-max 21 Ø21 mm
- System Reduction: 2900
- Estimated mass of housed actuator system: 344 g

Configuration for driving actuators:

- Secondary gear stage: HarmonicDrive AG CPL-2A-17 100
- Primary gear stage: Maxon planetary gearhead GP 16M Ø16 mm
- Motor: Maxon RE-max 17 Ø17 mm
- System Reduction: 2900
- Estimated mass of housed actuator system:

	weight [g]	Reduction	Comment
HD gear	100	100	CPL-2A -17 100
Planet gear	28	29	Planetary Gearhead GP 16 M Ø16 mm, 0.1 - 0.3 Nm, 312912
Motor	26		RE-max 17 Ø17 mm, Graphite Brushes, 4.5 Watt (216004)
output housing motor & HD	70		
Housing	60		
bearing	80		
Encoder	15		Maxon MR
sealing s/s	20		
interface	50		
SUM	**449**	[g]	

Table 11-10: Mass assumption for one Driving Actuator

Motion controllers

The Mass and the package sizing for the motion controllers are based on the ExoMARS ADE (Actuator Drive Electronics).

11.1.4 Power Estimation

The power estimations are made with the Rover Parametric Evaluation Tool developed by RUAG Zurich RD[24] under ESA contract.

The software allows the full simulation of a 6 wheeled three bogie traversing different terrain types and obstacles [see Figure 11-6, Figure 11-2 and Figure 11-8].

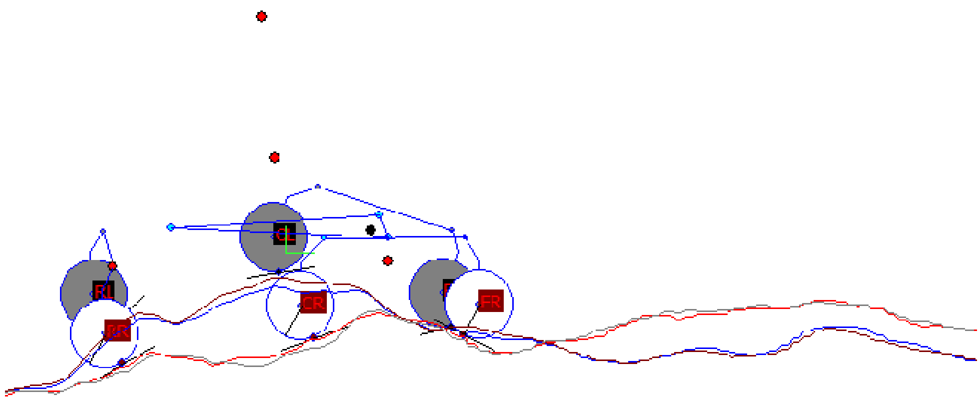


Figure 11-6: Rover traversing a terrain; simulated in the RUAG RPET tool

Terrain specification for the "semi rough" terrain:

Figure 11-7: Elevation map of the test terrain (bright= low terrain, dark= high terrain)

Note: Low corresponds to local zero altitude and black is 1 m (also local) not taking the global slope into account.

Figure 11-8: Soil distribution on test terrain (white= soft, grey=medium, black= hard)

Terrain type	Wheel speed [m/s]	Speed (Rover) [m/s]	Energy consumption per meter [Wh/m]	Average Power-consumption [Watt]
0° slope on flat sand	0.011	0.0099	0.325	
20° slope on flat sand	0.011	0.0044	1.747	
minus 20° slope on flat sand	0.011	0.0134	0.315	
rough terrain	0.011	0.0077	0.829	
Semi rough	0.003	0.0024	0.640	5.53
Semi rough	0.008	0.0069	0.468	11.62
Semi rough	0.011	0.0098	0.467	16.48
Semi rough	0.015	0.0133	0.455	21.78
Semi rough	0.018	0.0163	0.439	25.75
Semi rough	0.021	0.0192	0.426	29.67

Table 11-11: Energy and Power for simulated terrains, (values including efficiency of gears, efficiency of motors and a safety factor)

Table 11-11 shows the energy and power consumption in different terrain types. The 20° slope case give the driving parameter for the peak power consumptions and the "Semi rough" terrain at 0.021 m/s commanded speed gives the average power consumption for the nominal driving without the ADE's power consumption. It is also visible, that the energy consumption per meter is decreasing with a higher velocity.

11.1.5 List of Equipment and Mass Budget

Table 11-12 summarises the masses of the equipment described previously in this document to calculate the total mass of the locomotion system.

Component	***Unit mass (g)***	***Quantity***	***Total mass***	***Maturity margin (%)***	***Mass Estimation with margin***
Wheel	1.15	6.00	6.92	20.00	8.31
Driving actuator	0.45	6.00	2.70	20.00	3.24
Steering actuator	0.35	6.00	2.10	20.00	2.52
Side bogie beam	1.00	2.00	2.00	20.00	2.40
Rear bogie beam	1.00	1.00	1.00	20.00	1.20
Harness	1.04	1.00	1.04	10.00	1.15
Motion controller	0.21	36.00	7.38	20.00	8.86
Deployment actuator	0.45	6.00	2.72	20.00	3.27
Total			**25.87**		**30.94**

Table 11-12: Mass budget

11.2 Robotic Arm

A robotic arm is required on the rover to support the several operations with different instruments.

11.2.1 Requirements

11.2.1.1 Loads

The arm will be the link between the rover and the following instruments:

- Close-Up Imager (CLUPI) 1 kg
- Mössbauer spectrometer 0.6 kg
- Corer 0.7 kg

The total mass at the arm tip is 2.3 kg in a gravity environment of 3.71m/s^2. This 2.3 kg is the payload mass. Although the gravity of Mars is lower, the initial calculation for the basic parameters of the arm uses Earth's gravity. The actual tests on Earth can be performed with a reduced payload.

11.2.1.2 Tasks

The CLUPI shall take several pictures of the science subject, the Mössbauer spectrometer shall be pressed against the soil to do science and the Corer shall be able to take a sample of the soil and store it into the OSL. These three functions are fully separated. The robotic arm shall be the interface between these instruments and the rover. The CLUPI shall be orientated away from the corer to protect the lens of the camera during the drilling operation.

11.2.1.3 Accuracy

The accuracy of the arm shall be better than one cm at the tip of the arm to ensure the CLUPI is able to take a picture of the desired location. The stiffness and stability are not considered during this preliminary design. This should be analysed in the next stages.

11.2.2 Robotic Arm Description

A kinematic analysis has been performed to design the kinematic structure of the arm. The arm should fit the requirements summarised above. Two limbs of different sizes are used to have a compact arm in stowed situation and to be able to cover the required sampling area. Four joints are providing the arm four degrees of freedom to perform the operations without colliding with other pars of the rover. There is one vertical joint (J0) which allows the arm to move in the horizontal plane and there are three horizontal joints (J1, J2 and J3) to move the arm in the vertical plane.

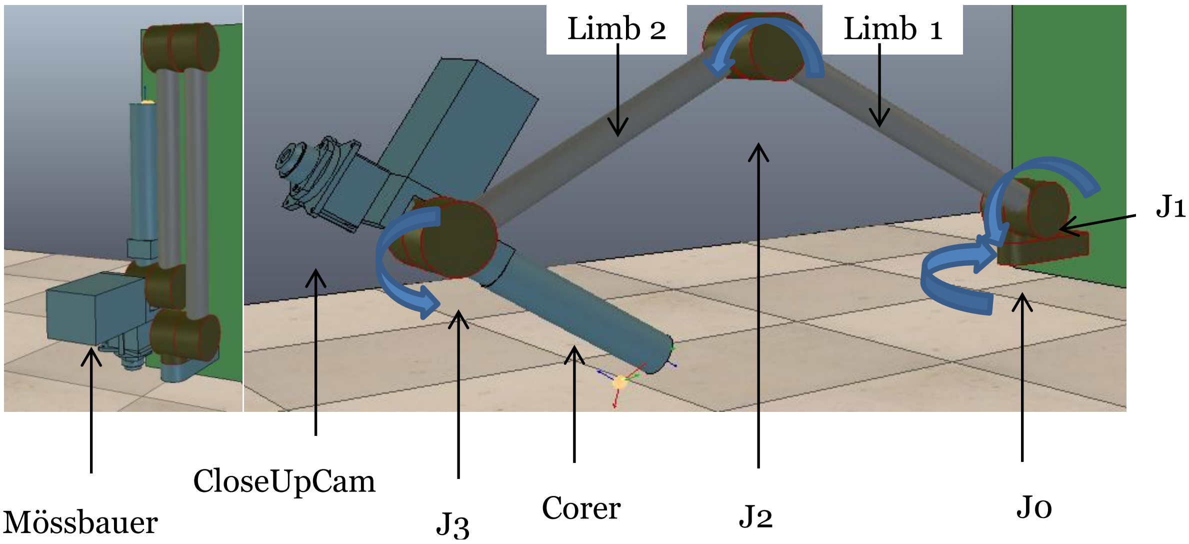


Figure 11-9: Arm description

The fact that the arm is mounted on a moving platform could be used to remove the base joint (J0) and use the point turn locomotion mode as another degree of freedom. This is considered and would result in a lighter 3DOF arm. However this setup will be much less accurate. Therefore the 4 DOF's are kept as the baseline.

11.2.2.1 Sampling radius

The sampling radius of the robotic arm is 450mm. The sampling surface is shown in the following picture marked by the blue line. This area can be increased by shifting the base of the robotic arm a bit more to the front so the arm will reach further than shown in Figure 11-10. This is an option as long as the arm does not collide with the mast or the Direct To Earth (DTE) antenna.

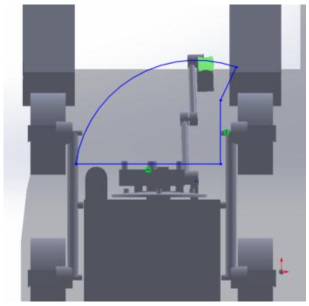


Figure 11-10: Sampling radius

11.2.3 Arm Calculation

11.2.3.1 Limbs:

The limbs have to be strong enough and therefore a calculation will provide an estimation of the weight of one limb. The limbs will be made from lightweight aluminium beam with an outer diameter of 25mm, 2mm thickness and have to withstand a bending moment of 5 Nm. This bending moment is produced due to the mass of the payload (mp) and the length of the limb.

Mb≡ bending moment

g ≡ gravity on Earth

l ≡ length of the arm in extended position

I ≡ moment of inertia

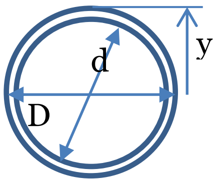


Figure 11-11: Limb section

$$Mb = mp * g * l$$

$$\sigma = \frac{Mb * y}{I}$$

$$I = \frac{\pi * R^4}{4} - \frac{\pi * r^4}{4} = 9.62 * 10^{-9} m^4$$

σmax = $1.21*10^{10}$Pa

σalu = $7 * 10^{10}$Pa

The aluminium thin-walled beam is able to withstand the small forces produced by the payload.

<u>Mass</u>

The limbs are made of hollow cylinders with an outside diameter of 25mm and inner diameter of 21mm. The lengths of the limbs are 0.3m and 0.26m. The density (ρ) of the aluminium is 2800kg/m^3

$$V = \frac{\pi * (D^2 - d^2)}{4} * l = 4.33 * 10^{-5} m^3$$

$$m = V * \rho = 0.121 kg$$

Limb 1=0.121kg

Limb2= 0.105kg

11.2.3.2 Joints

In this mission the robotic arm will have several load cases. The worst load case will be used to determine the required torques. Earth's gravity will be applied designing the arm to be able to test the operations in a terrestrial environment. The worst load case can be found in the following figure.

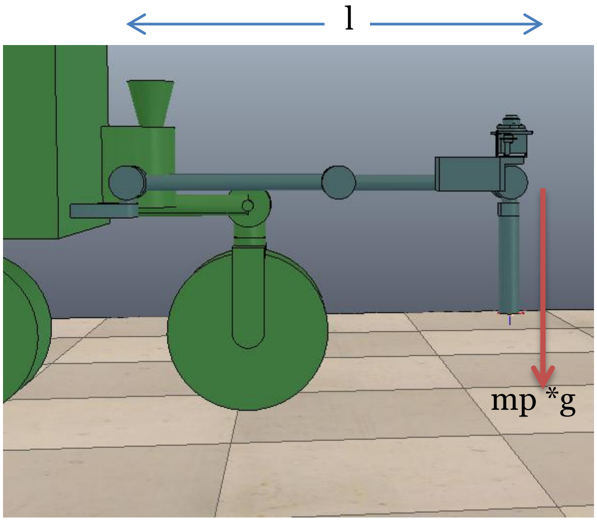


Figure 11-12: Arm fully extended

The required torque is dependent on the load of the payload and on the mass of the arm itself. This is because J1 should be able to carry the load of the payload and the load of the arm itself as well. Therefore several iterations were required.

To estimate the weight of the joints it is valuable to refer to the scalability analysis which is reported in document RD[22] from the ESA DELIAN Arm project. Four families of joints have been identified, covering all DELIAN application scenarios. They have been preliminarily sized in terms of torque, mass and dimensions.

Torque and mass are related as shown below:

- 0 - 4 Nm, 0.356 kg
- 5 – 12 Nm, 0.438 kg
- 13 – 40 Nm, 0.585 kg
- 40 – 75Nm, 1.04 kg

The load on J0 is perpendicular on the movement of the joint. Therefore the motor doesn't have to be designed with respect to the load. This torque is required to only start the motion and overcome the bearing friction without wearing big loads. Therefore it can be neglected. J3 doesn't have to take a big load in the worst case but has to counter react torque 2 during drilling. Therefore those joints will be sized equally.

Variable	Value	Unit	Description
mJo	0.453	kg	Mass joint 0
mJ1	0.585	kg	Mass joint 1
mJ2	0.453	kg	Mass joint 2
mJ3	0.438	kg	Mass joint 3
Mlimb1	0.121	kg	Mass limb 1
Mlimb2	0.105	kg	Mass limb 2
l1	0.3	m	length limb 1
l2	0.26	m	length limb 2
l	l=l1+l2	m	total length
mp	1.7	kg	Mass payload
g	9.81	m/s^2	gravity Earth
gm	3.711	m/s^2	gravity Mars

Table 11-13: Equation variables

$$TJ1 = mJ2 * g * l1 + mJ3 * g * l + mp * g * l + Mlimb1 * g * \left(\frac{l1}{2}\right) * l + Mlimb2 * g * \left(l1 + \left(\frac{l2}{2}\right)\right)$$

$$TJ2 = mJ3 * g * l2 + mp * g * l2 + Mlimb2 * g * \left(\frac{l2}{2}\right)$$

TJ1= 13.7Nm

TJ2= 5.6 Nm

The arm will be able to take the weight of the payload when it needs to overcome the maximum torque. There are two torque cases they should be considered: The first one is already described above considering the arm is fully extended and the second one shall occur while drilling. A small drilling force (Fd) should be exerted on the Martian surface during the drilling procedure. The weight of the payload can already generate this small force and the torque of J1 over the distance can be added.

Fd= Mp * g_m + TJ1/l = 30.75 N

This is way more than the required value for the drilling force which is below 10N.

11.2.4 Motors

The choice of the actuator has been taken following the outcome of the trade-offs of the ESA DELIAN technology development RD[22]. Brushless D.C. torque motors appear to be the best option for this type of robotic arm. **Motor controllers**

One motor controller has a mass of 0.1 kg. The weight is estimated by a scaled down approach from the ExoMars electronics due to the smaller power demand. The arm will use 4 motors which require 4 motor controllers. These controllers can be stored inside the controller box for the locomotion subsystem.

11.2.4.1 Harness

Whether the harness is internal or external to the arm structure, the torque necessary for bending and twisting of cables can be substantial at the low temperatures expected on Mars. Especially with high rotation angles (>90° deg) the bending torque resistance of normal electric wires increases significantly.

Flex printed circuit harness is a solution for minimising resistive torque. Referring to annex III of the DELIAN arm RD[22] the resistive torque of the Flex print is only 0.03 Nm for 24 wires. This torque is negligible with respect to the torque used in the joints.

With respect to mass, in this phase of the mission design, the mass of the harness is conservatively estimated as 10% of the total robotic arm mass.

11.2.4.2 Thermal protection

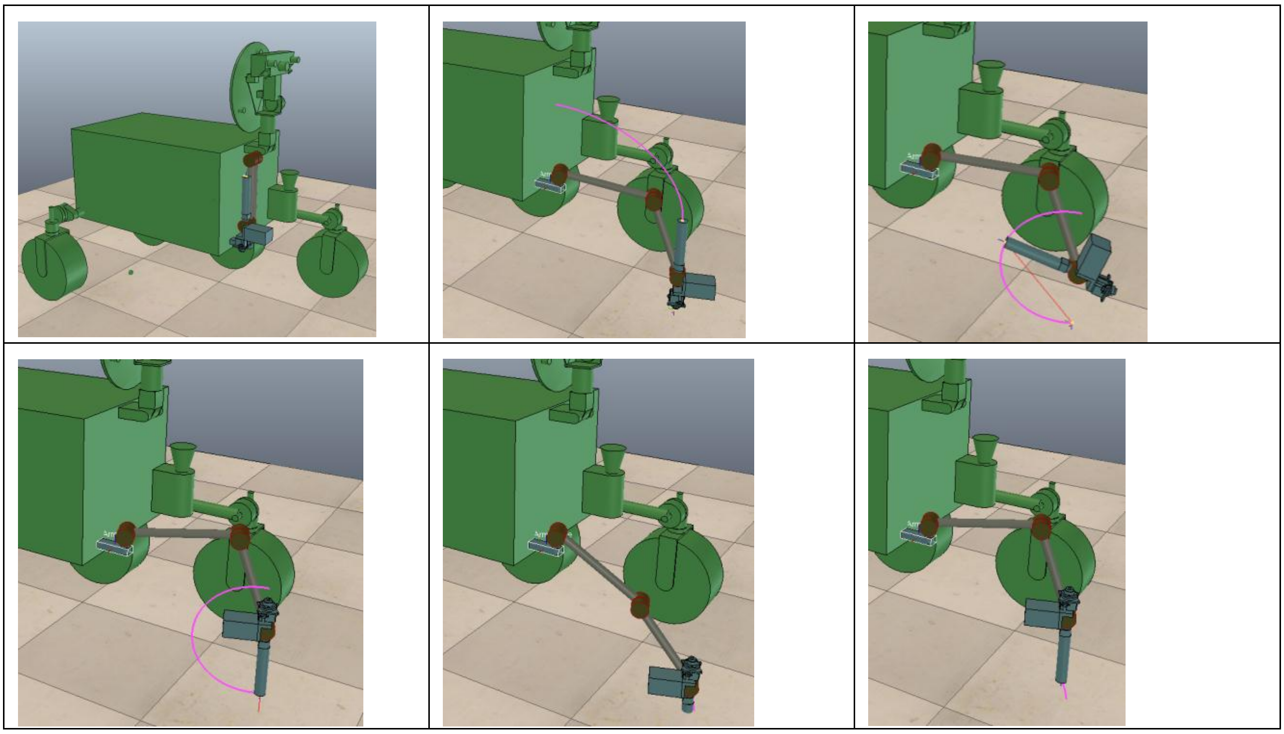
The thermal protection is estimated as 5% of the total robotic arm mass.

11.2.5 Operations Sequence Sampling

The robotic arm is stowed in front of the rover body to be able to use the front cameras to investigate the science area. It is attached to the rover body with two HDRM's. Finding an interesting science spot can be followed by the following sequence:

1. HDRM's are released
2. The arm brings the CLUPI close to the soil to take pictures of the sampling area.
3. The arm turns the payload tool around in order to bring the corer in position just above the soil after which the corer starts the drill.
4. The payload goes down in a straight line to start drilling.
5. The arm goes back up in a straight line.
6. The arm brings the sample to the funnel and the corer drops the sample
7. The arm goes back into stowage position.

This sequence is illustrated below:



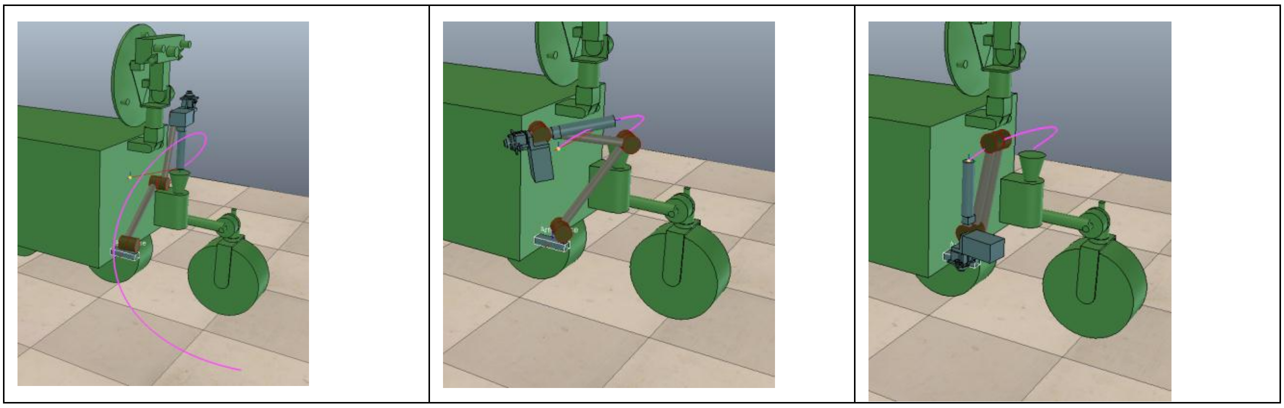


Table 11-14: Sampling sequence

11.2.6 Operations sequence Mössbauer spectrometer

The following sequence can be used when an interesting science opportunity is found for the Mössbauer spectrometer.

1. The arm moves slowly down until it touches the soil.
2. The spectrometer can perform the science while the arm is pressing the spectrometer against the soil.
3. The arm goes back in to stowage position.

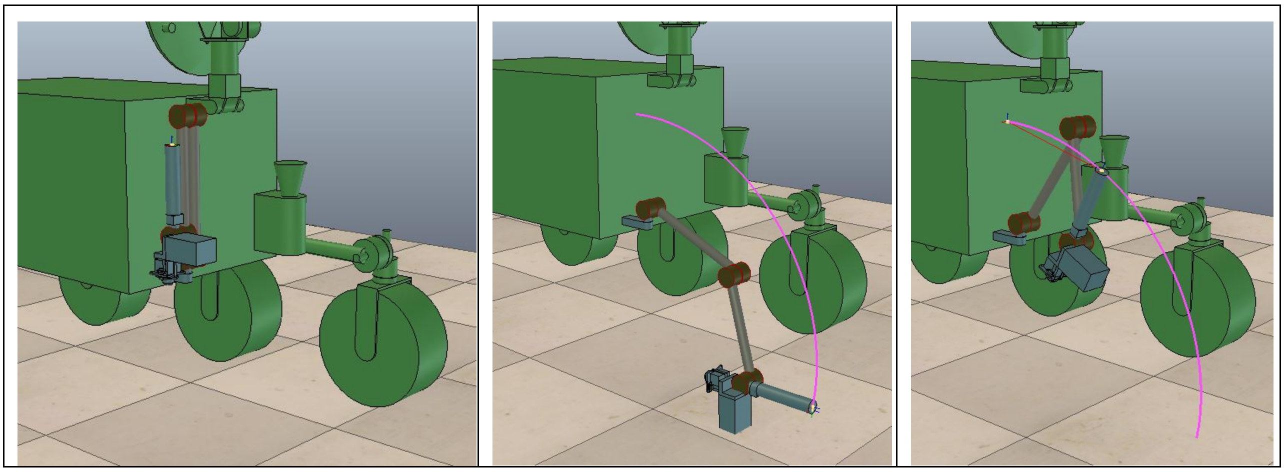


Table 11-15: Mössbauer operation sequence

11.2.7 Mass Budget

The total mass of the arm is the sum of the masses of the joints, the limbs, motion controllers, the harness and the thermal protection. The harness and thermal protection are typically 15% of the arm mass.

Variable		Value	Unit
Mass joint 0		0.453	kg
Mass joint 1		0.585	kg
Mass joint 2		0.453	kg

Variable	Value	Unit
Mass joint 3	0.438	kg
Mass limb 1	0.121	kg
Mass limb 2	0.105	kg
Total bare mass	2.17	Kg
Harness and thermal protection15%	0.3255	Kg
4 motor controllers	0.4	kg
Total mass ex. margin	**2.89**	**kg**
Total mass incl. 10% margin	**3.2**	**kg**

Table 11-16: Arm mass budget

The total mas of the robotic arm including 10% margin is 3.2kg.

During cruise and roving, the arm shall be attached to the rover with at least two hold down and release mechanisms. These HDRM's are described in the mechanisms chapter.

11.2.8 Power Budget

The joints, including motor controllers, will typically consume 1.5 watt with an efficiency of 0.6 during operation.

$$\left(\frac{1{,}5watt}{0.6}\right) * 4joints = 10watt$$

The robotic arm consumes an average power of 10 watt at some points in the science stop long (SSL) mission mode.

11.3 Technology Requirements

The following technologies are required or would be beneficial to this domain:

Included in this table are:

- Technologies to be (further) developed
- Technologies available within European non-space sector(s)
- Technologies identified as coming from outside ESA member states.

Equipment and Text Reference	Technology	Suppliers and TRL Level	Technology from Non-Space Sectors	Additional Information
Robotic arm	Payload manoeuvres	TRL 4 DELIAN activity	Yes	Heritage from Beagle 2 robotic arm.
Locomotion system	Triple bogie	Used in ExoMars TRL above 4	-	Wheel walking has TRL 3

12 ROVER VALIDATION & VERIFICATION

This chapter explains the approach on how to validate and verify the mobility and navigation capabilities. It also shows the limits of what can be done on Earth and what needs an actual Mars mission. This is of particular interest for the MarsFAST mission as it will serve to reduce the risks of failure during the MSR fetching rover mission.

Definition:

- **Validating a system**: Building the *right system*: making sure that the system does what it is supposed to do in its intended environment. Validation determines the correctness and completeness of the end product, and ensures that the system will satisfy the actual needs of the stakeholders. (see RD[27])
- **Verifying a system**: Building the *system right*: ensuring that the system complies with the system requirements and conforms to its design. (see RD[27])

To reduce the testing complexity it is essential to break down the functionality of the design into modular components that can be tested more thoroughly as subsystems and then constructed together into the overall system to perform testing on the integrated system.

- Non autonomous part: Locomotion Verification Model existing actuator drive electronics and the electro-mechanical bogie assemblies to test locomotion requirements
- Autonomous part: Algorithms are tested in a "Numerical Software Validation Facility" + tests with Electrical Test Model in lab and outdoor terrains.

Strategy for each sub-system:

1. Specify Requirements in detail level
2. Validate Requirements
3. Verify technical solutions

For a validation of the set of stated requirements, a full mission simulation is necessary. For this phase of the study, this is not done. However, the worst case situations are analysed and used as baseline for the system layout.

The following verification solutions are not formulated in a full "verification matrix".

Also, there is no post mission disposal foreseen.

12.1 V&V for the Mobility Capabilities

12.1.1 Mobility Requirements:

Clarification: The Rover shall be able to

MR-10	Drive 28 km on Mars terrain without mechanical failures
MR-11	Overcome steps of 20 cm height with a vertical slope
MR-12	Traverse a 5° slope on ES1 -4 below 50% slippage
MR-13	Acquire enough energy to drive the required distance/day
MR-14	Have a nominal speed greater than 1.8 cm/s

MR-15 Egress the lander in a worst case landing configuration
MR-16 Traverse a 20° slope on ES3 below 90% slippage
MR-17 Have an average slippage below 25% over the whole driven distance

12.1.2 Mobility Requirements Test Proposals

The following explains the test procedures needed to verify the given requirements in paragraph 12.1.1 .

MR-10: This requirement is not completely verifiable on Earth. The subsystems wheels, actuators and suspension can be tested in specifically generated environments.

MR-11: This can be tested with a weight wise scaled model (to address the diffenence in gravity) of the Rover on different rock types in a soil test bed on ground.

MR-12: This formulation allows a full verification with a weight- scaled model of the Rover on an angled soil test bed.

MR-13: For that, the full system has to be tested as one unit in a long term field-test. This requirement can be diversified in smaller subsystems. Then, the degradation of the solar arrays including the dust accumulation, the increased friction due to wear in the actuators, and the energy loss in the wheel soil interaction have to be partly verified.

MR-14: The nominal speed can be verified, once the wheel soil interaction is tested in more detail and more precise slippage values are delivered.

MR-15: The worst case lander configurations can be fully reproduced on ground and tested with a weight- scaled model of the Rover.

MR-16: This formulation allows a full verification with a weight- scaled model of the Rover on an angled soil test bed.

MR-17: The average slippage can be verified, once the wheel soil interaction is tested in more detail and more precise slippage values are delivered. This also depends on the choice of the landing site. A simulation campaign is necessary for this verification.

12.2 V&V for the Navigation Capabilities

12.2.1 Navigation Requirements:

System requirements:

NR-10 The Rover shall have an ECSS Autonomy level ≥E3 (see RD[28])

Localization Requirements: The Rover shall be able to:

NR-11 Have less than 1% of error in final position at the end of one traverse stint
NR-12 Have less than 5% of error in heading at the end of a traverse stint
NR-13 Have less than 0.5 % of error in heading at the beginning of a traverse stint
NR-14 Get correction via global positioning done by a Ground Control Station

Navigation Requirements: The Rover shall be able to:

NR-15 Autonomously detect a trap situation
NR-16 Autonomously stay away more than 0.8 m from non-traversable areas

Path Planning Requirements: The Rover shall be able to:

NR-17 Communicate with a global planner in the Ground Control Station
NR-18 Plan 4 m ahead with its integrated local path planner

12.2.2 Navigation Requirements Test Proposals

NR-10: The E3 autonomy can be verified in simulations and/or a field-test with a test Rover

NR-11: The error in the final position can be tested in a field-test with similar terrain conditions to Mars.

NR-12: The heading error is generated by the Rovers internal odometry and the error of the sun sensor. The odometry part is possible to test in a semi representative environment, like a dessert. The sun-sensor cannot be fully verified on ground due to different atmospheric conditions.

NR-13: The heading at the beginning of a stint is corrected by the sun sensor. Optional, gyro-compassing during the night with the IMU can reduce the error. Verification on ground is difficult.

NR-14: The correction via Ground Control Station can be verified by inspection plus communication analysis.

NR-15: The autonomous detection of a “trap situation” is fully testable on ground, using a sand test bed.

NR-16: The autonomous safety distance is fully testable on ground, using a sand test bed including different obstacles.

NR-17: The communication with Ground Control Station can be verified by analysis.

NR-18: The local path planner can be fully verified in a rover model tested in different environments.

12.3 Support Equipment and Facilities for Verification

12.3.1 Thermal Vacuum Chamber

The thermal vacuum chamber and representative Mars atmosphere is necessary to simulate a representative environment for identifying wear in the motors and gears. It is also used to identify the energy losses due to the use of lubricants in Mars temperature ranges.

12.3.2 Soil Test-Bed with Variable Slope

The Test-bed contains a vision system for the position recognition, a DEM (Digital Elevation Model) system, a variety of soil types and boulders

12.3.3 Weight-Scaled Rover

One weight scaled model with the real locomotion dimensions is necessary for all locomotion tests.

12.3.4 Single Wheel Test-Bed

A single wheel test-bed can be useful for subsystem verification of the wheel soil interaction in different situations.

12.3.5 Navigation Rover

For the navigation verification, a vehicle with representative locomotion capabilities and vision hardware is required.

12.4 Discussion on the need for an intermediate Mars mission to verify MSR fetching rover technologies

From the analyses presented in this report it can be inferred that – despite intense on-ground validation and verification – the MarsFAST mission would limit the risk of failure for the MSR fetching rover mission for what concerns:

- Fast mobility: wheel to soil interactions understanding, navigation sensors performances under real environment, ???
- Other subsystems: optimised sizing of thermal and power subsystems based on operations in real environment over a representative time frame.

While it could be debated that such an intermediate mission is required for sure, it should be considered as an efficient way to reduce the risks of a much more costly mission.

Moreover, the fast mobility capability would be useful to any other future mission requiring to access several sites, as it will limit the risk of mission termination before fulfilling all the science objectives.

13 NAVIGATION

13.1 Requirements and Design Drivers

From the mission requirements it is derived that for the worst case scenario the rover will need to traverse a total ground track distance per sol of 255 m (for a traversability factor of 1.4), which considering 4h of traverse per sol requires the rover to navigate on Mars at an average speed of 1.8 cm/s. This and the rest of the subsystem requirements that are derived from here are detailed in the table below:

Subsystem requirements		
Req. ID	**STATEMENT**	**Parent ID**
NAV-010	The rover shall navigate at an average speed of 1.8 cm/s	
NAV-020	The rover shall have an ECSS Autonomy level ≥E3	
NAV-030	Have less than 1% of error in position	
NAV-040	Have less than TBD m of absolute error in position anytime during traverse	
NAV-050	Have less than 5 % of error in heading at the end of a traverse stint	
NAV-060	Have less than 0.5 % of error in heading at the beginning of a traverse stint	
NAV-070	Get corrections in position via Ground Control Station through a global positioning system	
NAV-080	Get navigation waypoints via Ground Control Station	
NAV-090	Autonomously detect a trap situation	
NAV-100	Autonomously stay away >0.8 m from non-traversable areas	
NAV-110	Autonomously perform local path planning over the mapped area in front	

Table 13-1: List of requirements

13.2 Assumptions and Trade-Offs

Solutions for autonomous and accurate navigation of rovers have a strong dependency on exteroceptive visual sensors.

Odometry based on wheels and inertial sensors is known to have significant drift on unstructured and/or unknown terrains and this would hardly fulfil the mobility requirements of this mission for its dead reckoning phase.

Time of Flight (ToF) cameras and/or Light Detection and Ranging (LiDAR) sensors were not seriously considered in the study given the lack of heritage and of space qualified solutions for rover navigation systems. Therefore, the selected solution is based on the perception of the environment by means of several sets of cameras.

Navigation consists of an iterative process of Mapping, Localisation, Planning and Actuation. This process needs to be optimised given the mission constraints in resources, not only in mass and volume but also in energy and time. Derived from subsystem requirement NAV-010 the criteria to maximise mobility would be the actuation performance. By decoupling the locomotion performance from this, for the navigation subsystem the criteria to maximise would be just the actuation time (locomotion phase). Due to power constraints, rover navigation and actual traversing can only happen for a limited amount of time during the sol when the power generation of the solar arrays is maximum. From this and the challenging mobility requirements it is derived that the rover should stop as little as possible, and in the best case scenario don't stop at all.

Regarding the rover mapping, localisation and planning tasks, these can only happen at local level on-board the rover system. Generally, mapping capabilities will be limited to a few meters ahead and thus the planning over a traversable path can only be generated for the mapped area and updated along with motion (NAV-110). The same happens for the localisation where the estimated position will be relatively integrated from the previous –or initial– state of the rover (a.k.a. dead reckoning) and will be updated accordingly after motion. The process of localisation through camera image information is known as visual odometry and has the advantage of being unaffected by slippage and therefore be less prone to drift.

In order to translate from the local to the global plan it is assumed the existence of a high resolution map of the mission area in Mars, e.g., HiRISE maps. The performance of the rover navigation is very much dependant on this map since without a global path planning the rover would be exploring "aimlessly" trying to find its target, e.g. a cached sample, in a vast area of 314.1592 km^2. The global map will serve to: first, draw an optimised path (NAV-080) from the landing site to the cached sample –avoiding globally "non-traversable" areas and reducing re-planning – and second, enable rover global localisation during traversing and introduce periodical corrections to damp the drift in absolute positioning (NAV-070).

13.3 Baseline Design

The baseline solution for the navigation subsystem is based on the heritage of the SPARTAN activity (and ExoMars) and complemented with recent developments on miniature inertial sensors on a chip and with absolute sensor for the heading of the rover (corrections as for NAV-050 and NAV-060). Figure 13-1 gives a generic overview of the approached solution:

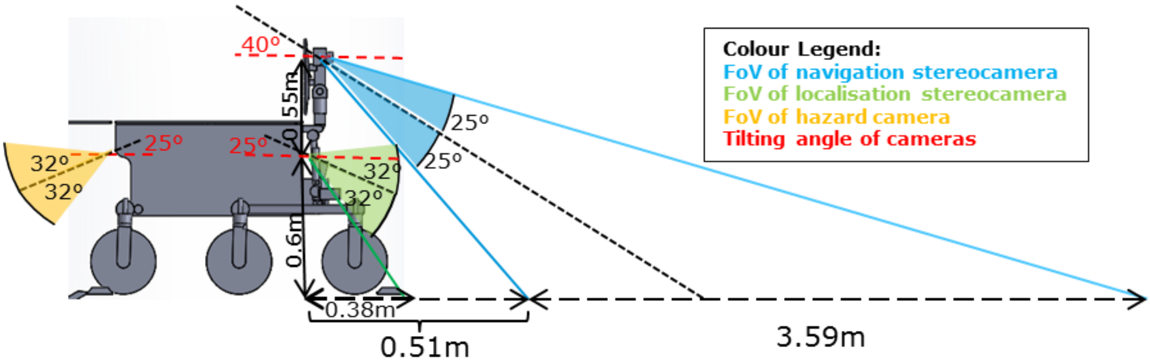


Figure 13-1: Overview of navigation subsystem

13.3.1 Mapping

A set of stereo cameras placed on top of the mast serve as navigation cameras and produce a map of 4m in range in front of the rover. An illustration of this is shown in Figure 13-2:

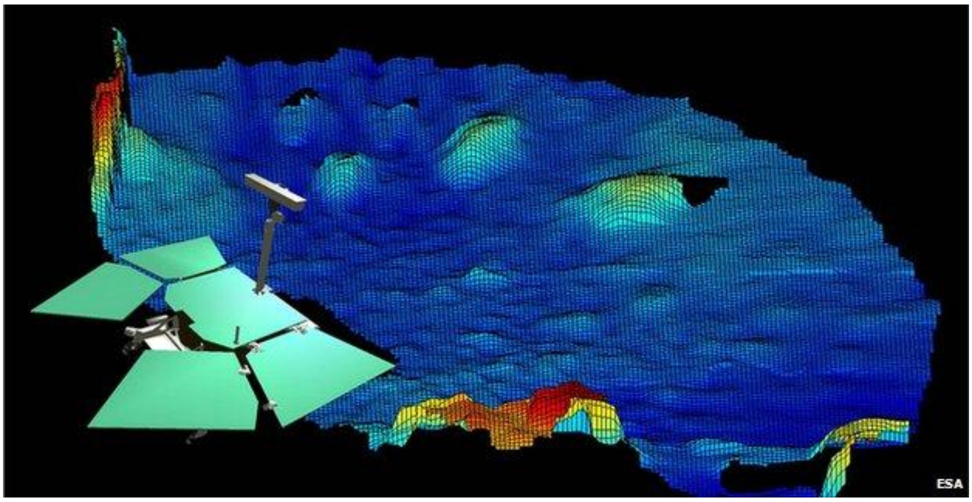


Figure 13-2: Illustration of map generation

The cameras have a FoV of 90° and given the dimensions of the rover it is decided to use a single stereo-pair for the generation of the DEM instead of panning the camera view and stitching several image pairs together to cover a wider FoV. This decision limits the performance of the path planning task which will generate a suboptimal path due to the reduced visible area that the rover can traverse to. However, given MarsFast rover dimensions, it generates a map wide enough to safely traverse a local path. As a trade-off, it also reduces the processing time and it does not require that the rover is stopped so that a set of stereo-pairs are acquired to generate the map. In fact, it enables a navigation strategy without stopping and therefore increases the fast mobility performance reducing the time and energy required to cover a given distance. Then, for the mapping and path planning task, it is assumed that the rover will be able to update the map and trajectory plan while still in motion, still allowing enough time to the on-board computer to calculate its next local navigation target before reaching the end of the mapped visible area. Finally, the path planner should find a local traversable path that avoids obstacles while aiming towards its next global navigation target (NAV-090 and NAV-100).

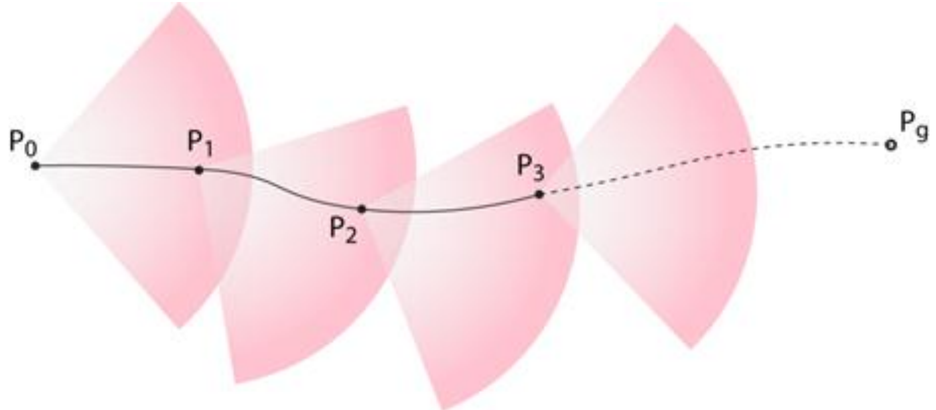


Figure 13-3: Example of map and trajectory generation

The equation below has been used to calculate some of the camera specifications:

$$l = \sqrt{\frac{0.5 * r * b * w}{c * \tan(0.5 * F)}}$$

Where,

$r \equiv resolution$
$b \equiv baseline$
$w \equiv horizontal\ resolution\ of\ the\ camera$
$c \equiv search\ range$
$F \equiv Field\ of\ View$
$l \equiv range$

This means for example that for a 90º FoV and a baseline (distance between camera lenses) of 20 cm, if we want to guarantee a resolution of at least 2 cm at a maximum range of 4 m, it will be required for the lenses to have a horizontal resolution of 2048 pixels.

Regarding the height at which the cameras are placed (top of the mast), there are several drivers that have an impact on this decision. On the one side, the lower the mast the more stable or rigid it becomes for a given allocated mass. Note that vibration could be an important source of error for not-stop mapping depending on camera exposure. Additionally, the lower the mast the better the image resolution as it decreases the distance to the target. On the other hand, the lower the mast the more relevant the shadowing effect of the obstacles becomes. The minimum height of the mast was estimated so that it limits the shadowing effect to those areas that the rover should not traverse due to the safety distance that it needs to keep from a given obstacle. Given the rover dimensions, this distance results in 0.8 m (NAV-100). Therefore the mast height shall allow an obscured area of no more than 0.8 m. Finally, the mast height that best fits the navigation purposes is 1.15 m above the ground level (see Figure 13-4):

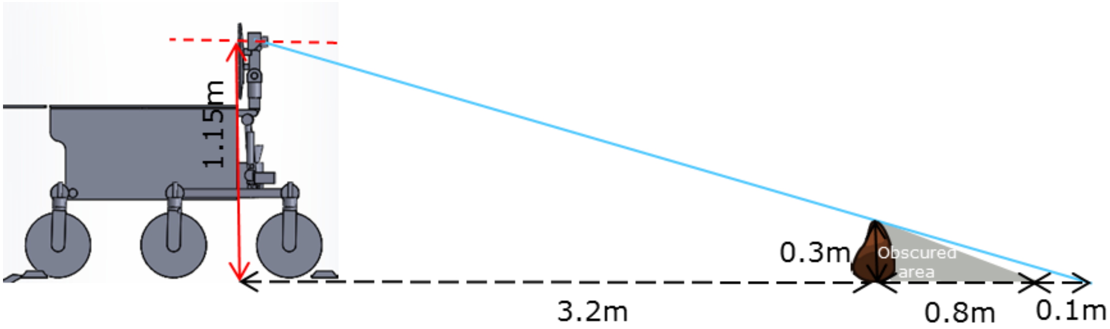


Figure 13-4: Mast height trade-off

13.3.2 Localisation

The second set of stereo cameras is placed at mid height of the rover (0.6 m) and serves as localisation cameras. These cameras are used to run the visual odometry algorithms that will update at a rate of 1Hz the estimated position and orientation of the rover. Basically, these algorithms compute the relative motion of detected features in consecutive camera views (see example in Figure 13-5) and then inversely estimate from them the rover motion, i.e., transformation matrix that best fits the aforementioned relative motion of all features. Compared to the navigation cameras these ones have a lower resolution and have a fixed orientation at a lower height. A good trade-off is to guarantee 1mrad per image pixel resolution.

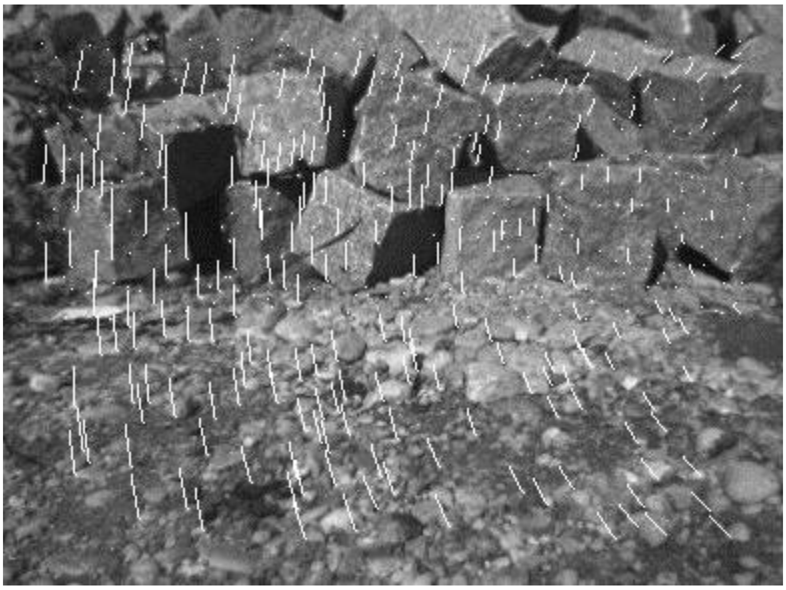


Figure 13-5: Example of tracking relative motion of features in the scene

13.3.3 Planning & Trajectory Control

Following the heritage of ExoMars the behaviour of these task modules is explained below.

The short-term (local) optimal path is calculated via a combination of an A* ('A-star') algorithm and a dynamics based path optimisation. The generated spline is then divided into a list of paths and point turns which is called the path sequence. This path sequence can then be sequentially fed into the trajectory control module.

Then, the objective of the Trajectory and Motion Control system is to drive the rover along a path that has been output by the Path Planning module. A path would typically be approximately 2-4 m long. At low level, the motion control transforms the vehicle level commands (eg. heading and curvature) into actuator level commands (wheel speeds and steering angles) in a synchronised way.

13.3.4 Global Frame

As mentioned previously, the rover navigation to the targeted cached sample would not be possible without a global perspective of the exploration area. Indeed, once the landing site is localised the control operations shall feed the rover with navigation waypoints (of few hundreds of meters apart) so that the rover does not lose time exploring unnecessary areas (NAV-080). Figure 13-6 depicts the trajectory traversed by the Curiosity rover during the first 665 sols on Mars. Note the little overlapping (no loop closure) and thus the relevance of periodic instructions from Earth.

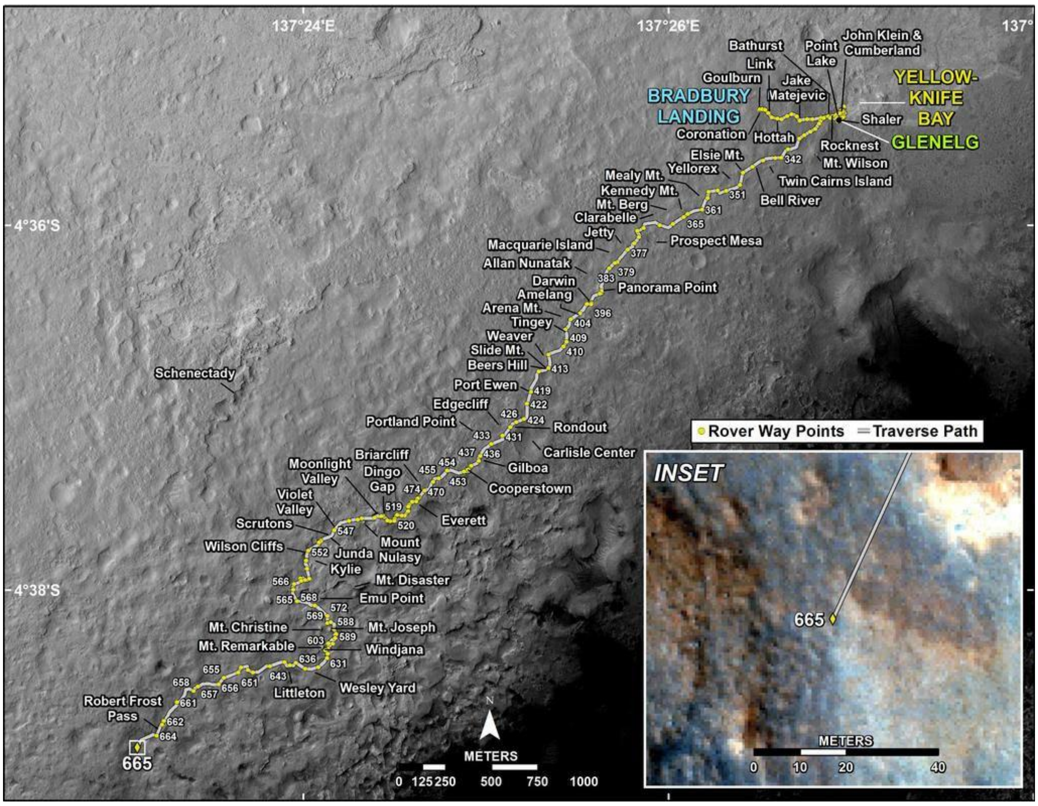


Figure 13-6: Path followed by Curiosity over the travers of 665 sols

It is also important to note that rover localisation by means of visual odometry while being unaffected by slippage is still an inertial method that gradually builds an error. This error is minimised by combining the information coming from other sensors like the IMU, wheel odometry or the sun sensor, especially to damp the error in heading and reduce further the drift (NAV-050 and NAV-060). Overall, the state of the art in localisation and sensor fusion gives an estimated localisation with 1-2% of relative error (NAV-030). Eventually, the longer the rover traverses, the bigger the absolute error in position. The accumulated drift after one sol of traverse would be in this case about 3-5 m (considering a traverse of 250 m/sol). Therefore, the permissible absolute error over the path traverse (NAV-040) will determine the frequency at which this error needs to be corrected by some external method, i.e., by means of ground control intervention.

Ground control techniques could again involve global navigation –localisation– corrections in order to reduce the accumulated pose drift. Different methods could be used to localise the rover in the global map. Generally, these methods try to match some identified feature between the images taken by the rover (locally consistent) and the high resolution map taken by the orbiter (globally consistent). While one could think of a feature as a given landmark in the Mars surface area, e.g., the tip of a mountain, features can also be as complex as certain combinations of rocks or a characteristic surface relief. The example in Figure 13-7 is a matching between the DEM generated by the rover navigation cameras and the orbital map, a.k.a. Iterative Closest Point (ICP) matching. The result of projecting the local into the global map using such techniques is shown in Figure 13-7.

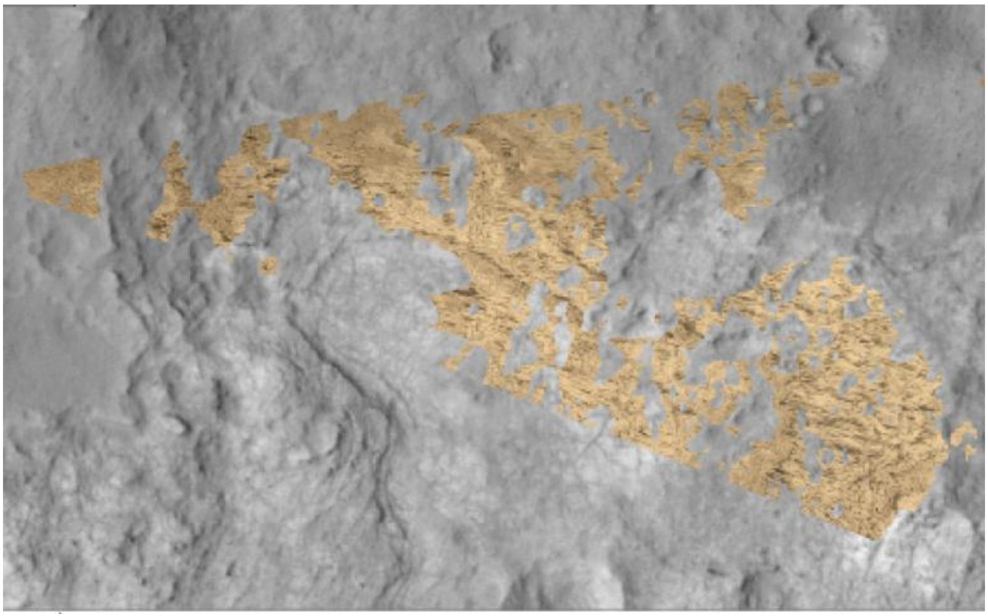


Figure 13-7: Example of ICP matching for global localisation

13.3.5 Data Budget

The amount of data to be sent to Earth will be dependent on the navigation requirements, the corrections in absolute position (NAV-040) and the confidence in the navigation subsystem performance (NAV-030). Below is an estimate of the amount of relevant data that should be transmitted per sol (housekeeping data excluding telemetry or sensorial data):

- LOCALISATION: Rover position (6 DoF) at 10 cm resolution
    - **0.5 Mbit/sol** (consider increasing resolution to 5 cm and use 1 Mbit/sol)

- MAPPING (also serves for global localisation corrections):
  - **32 Mbit/sol** for a set of 4 panorama pictures. Considering each panorama has 30m radial coverage with 1m accuracy. Provides an image view of the whole traversed distance (250 m). If only last panorama is to be sent 8 Mb/sol would suffice. However, this is not recommended
- DEM (OPTIONAL): Digital elevation map of the traversed path at 5 cm resolution
  - **1 Mbit/sol** (consider increasing resolution to 2 cm and use 5 Mbit/sol).

Note that a compression factor of 1/16 for the panorama images and ¼ factor for the DEM is considered. It is also likely that the Mapping/DEM and science data will be redundant.

13.4 List of Equipment

Table 13-2 shows the equipment with the corresponding mass and power budgets. The numbers include the maturity margin but do not include any system margin:

Element	Mass (kg)	Power (W)
Navigation Cameras (x2)	0.44	1
Localisation Cameras (x2)	0.44	1.5
IMU (x2)	0.6	0.8
Sun Sensor (x1)	0.24	0.2
Hazard Camera (back) (x1)	0.22	0.5
Total (incl. mat. margin)	2.1	4.0

Table 13-2 : List of Equipment with Mass and Power budgets

13.5 Options

The options for the navigation subsystem basically consist on the level of redundancy that is required.

There is already enough redundancy for the cameras, also considering there is an additional set of stereo cameras for scientific purposes (Panoramic cameras). In case of failure some cameras could cover the task of others (in a degraded mode) so it does not show a single point of failure. This is for example the reason why the vertical field of view of the localisation cameras is bigger and can cover a wider area.

Failure in the sun sensor can be covered by the IMU (degraded, non-absolute measurement of the heading) or even by the cameras which have been proved to be able to detect the orientation of the sun once they are roughly pointed towards it.

Lastly, it is recommended to have overall in the rover system two IMUs to cover the redundancy on this sensor. In case this is not possible due to mass restrictions we would highly encourage to have as a minimum additional accelerometers for pitch and roll estimation. The added mass to the system in this case would be around 0.1-0.2 kg depending on technology.

13.6 Technology Requirements

The following technologies are required or would be beneficial to this domain:

Equipment and Text Reference	Technology	Suppliers and TRL Level	Technology from Non-Space Sectors	Additional Information
FPGA	Space qualified powerful FPGAs RD[31]	No suppliers in Europe.	Powerful FPGA exist in non-space sector.	Possible suppliers in America
Vision based navigation (SPARTAN)	Low computation vSLAM	GMV TRL 3		Successive projects within the activity: SEXTANT and COMPASS. RD[29]
IMU	MEMS IMU on a chip	Colibrys Ltd. TRL 3		Internal project reference Stephen Airey. RD[30]

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14 POWER

14.1 Requirements and Design Drivers

The challenge of MarsFAST Rover power system is not only to provide necessary power for the science operation and for the rover motion, but also to support the thermal subsystem to maintain the minimal survival temperature in the Mars surface environment, given the fact that nuclear power systems are prohibited.

The thermal and power system sizing is highly dependent upon the latitude of the rover and the solar longitudes that must be considered within the mission scope.

In this CDF assessment the 2024 launch date has been considered.

2024 opportunity: Arrival Ls ~140, late N summer, ~2.5 months before start of global dust storm season.

The related optical depth profile is the one summarised in Table 14-1. The number of Sols is also shown.

Ls	No. sols	OD
140-180	74	0.5
180-192	20	1
192-220	6	1
192-220	40	1
220-246	40	1.5
	Tot= 180	

Table 14-1: Ls profile and Optical depth (OD)

The power system design is based on the Traverse Sol reference scenario, considering conditions after 110 sols (Ls 193, 20N), which is the rover "*end-of-life*" considered for the MarsFAST mission MSR fast mobility demonstration timeframe (i.e. in this reference mission scenario the fast roving capability demonstration has to be finished before the start of the solar conjunction and flawless traversing has to be practiced in advance, the 10 sol fast roving demonstration starts at sol 101.(see 7.3.4 for more details).

14.2 Power System Technology

For the solar panel, 3G30 cells are considered as baseline. Nevertheless current activities are running on "Next Generation Solar Cells With 33% Target Efficiency", which will be finished in 2015 and will also be continued by a follow-on activity. These activities are targeting to have a new cell ready for qualification in 2016. No dust deposition removal system has been considered as baseline for the sizing due to its overall energy efficiency/system impact in a short mission duration like MarsFAST.. However, the use of an Electrodynamic Screen (see RD[32]) was considered during the study as option and led to a small increase in solar panels mass and a penalty in power available at the beginning-of-life due to opacity of the screen.

As for the battery technology, Li-ion cells is the baseline. In RD[33] a summary of the test performed on COTS secondary Li-ion cells to operate at low temperature for use on a Martian surface elements is reported. The main results shows that it is possible to utilise COTS cells for demanding low temperature operations, provided that the cell limitations are understood with associated qualification activities.

Furthermore, a high temperature fuel cell can be used for energy storage with large storage capacity utilising onsite carbon dioxide as reactant. This is considered a valuable possibility for Mars missions and it is summarised in RD[34]. This solution has not been implemented in the current MarsFAST power system design.

The Power Conditioning Unit (PCU) is based on an unregulated bus architecture, where the bus voltage follows the battery voltage. During night and battery recharge mode, the bus voltage varies with the state of charge of the battery. After being fully charged, the bus is in voltage control mode at a predefined value. The PCU comprises all functions for power control from the solar arrays or from the umbilical to the main bus and to the battery.

In detail the PCU part comprises the following functions:

- Regulation of the electrical power from the solar array sections by means of 1 Solar Regulator Module (SARM) with 3 hot redundant step-down converters
- Control of the solar regulator converters by means of a one failure tolerant Maximum Power Point Tracker arrangement
- Regulation of the electrical power from umbilical by means of redundant DC/DC converters
- Control of the voltage of a Li-Ion battery by means of a one failure tolerant Main Error Amplifier system which provides the reference current values for the SAR converters and the umbilical converters.

Figure 14-1 shows the Efficiency figures considered during the sizing, with E_{SAR}=94%, E_{DM}=92%, E_{SC}=98%, E_{SDC}=E_{SCH}=97%.

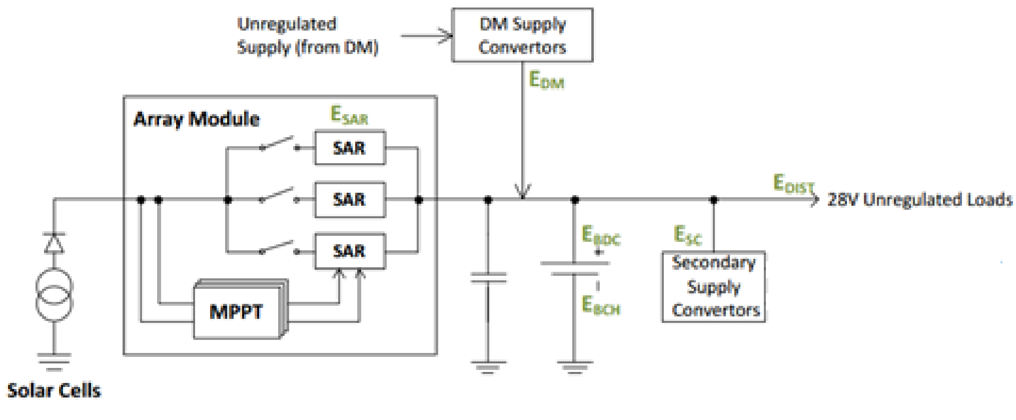

Figure 14-1: Rover Efficiency Model

14.3 Power System Sizing

The Traverse Sol reference scenario has been identified as sizing for the power system.

The power budget is shown in Figure 14-2.

		Thermal	Loc s/s	Comms	DHS	Mech	GNC	StereoCam	HiResCam	CloseUp Cam	OSL	ATR	MeteoPack	Mössbauer	Rob arm	PCDU	TOTAL CONSUMPTION
# 3 Traverse Mode	Pon	6.37900195	41	3	25 W		2.85						6			7	
	Pstdby	0	0	0	2 W		0						0			0	
	Duty Cycle	0 %	100 %	100 %	100 %		100 %						0 %			100 %	
	Paverage	0 W	40.98424	3	25 W		2.85						0 W			7 W	79 W
Tref 240 min	Total Wh	0	163.937	12	100 Wh		11.4						0			28	315 Wh
# 4 Science Stop Short Mode	Pon	6.37900195		3	14 W			10	10				10			7	
	Pstdby	6.37900195		27	2 W			0	0				0			0	
	Duty Cycle	100 %		100 %	100 %			100 %	100 %				100 %			100 %	
	Paverage	6 W		3	14 W	0	0	10 W	10 W	0	0	0	10 W	0		7 W	60 W
Tref 10 min	Total Wh	1.063167		0.5	2 Wh			1.66667	1.66667				1.66667			1.16667	10 Wh
# 7 Nominal Night Mode	Pon	12.15		26.4	14 W								6			4	
	Pstdby	0		1.5	2 W								0			0	
	Duty Cycle	100 %		1 %	1 %								0 %			100 %	
	Paverage	12 W		2 W	2 W								0 W			4 W	20 W
Tref 820 min	Total Wh	166.05		22.575	28 Wh								0			54.66667	272 Wh
# 8 DTE Communications Mode	Pon	4.25		133	14 W	10							6			7	
	Pstdby	0		6.3	2 W	0							0			0	
	Duty Cycle	100 %		14 %	100 %	3 %							33 %			100 %	
	Paverage	4 W		24 W	14 W	0.2857143							2 W			7 W	52 W
Tref 35 min	Total Wh	2.4791667		14.23333333	8 Wh	0.166667							1.155			4.08333	30 Wh
# 9 Idle Mode Day	Pon	6.37		26.4	14 W								6			7	
	Pstdby	6.3353		3.7	10 W								0			0	
	Duty Cycle	100 %		1 %	1 %								33 %			100 %	
	Paverage	6 W		4 W	10 W								2 W			7 W	29 W
Tref 370 min	Total Wh	39.281667		24.70833333	62 Wh								12.21			43.1667	181 Wh

Figure 14-2: Traverse sol Power budget

14.3.1 Solar Panels Sizing

For sizing the solar panels, a proper solar flux calculation on Mars surface is needed. An Excel based Mars solar power tool, previously developed at ESTEC, has been used for solar array power generation prediction. This model takes into account: the combined effects of illumination, local temperature, dust scattering and accumulation at Mars surface (based on extensive test data performed by Azur space and sub-co's in TRP contract 20509). The solar cells considered in this tool are the 3G28. Since a proper tool for 3G30 is not available yet, a small increase of 2.5% in solar cell efficiency has been considered with respect to the values calculated with ESA flux tool.

The parameter input sheet from the Excel tool is reproduced as in Figure 14-3. The values used were those in the figure, with the exception of latitude, Ls and optical depth, which were varied appropriately.

Dust deposition has been calculated using the "Pathfinder Model" as required by the mission requirements. It calculates the solar cells efficiency due to dust deposition vs. number of sols. The values are summarised in Figure 14-4.

1000	Number of photons launched per spectral band Ntir
150.00	**Ls Solar longitude (deg)**
20.00	**Latitude (deg)**
0.00	**Local True Solar Time (1 sol = 24 hrs ; 0 = midnight)**
0.20	Surface ground albedo (Spectrally integrated)
0	Surface spectral type (=0 : grey surface ; > 0 see user manual)
0.50	**Optical depth of dust at reference wavelength (0.67 micron)**
0.00	Optical depth of cloud layer at reference wavelength (0.67 micron)
0.40	Height of cloud (given by dust optical thickness below cloud)
1	Number of solar panel direction
0.00	**Zenith angle of normal vector to solar panel (deg)**
0.00	**Azimuth angle (deg) (northward=0 east=90 south=180 ...)**
1	Duration over which results will be given (in martian sols)
610.00	Ground pressure (ambient atmospheric pressure at ground level, Pa)
2.00	Visible (0.67um) to infrared (9um) dust opacity ratio
0.95	IR emissivity of bare ground
500.00	Thermal inertia of near-surface ground layer (J.s-1/2.m-2.K-1)
1000000.00	Volumetric heat capacity of near-surface ground layer (J.m-3.K-1)
30.00	Depth at which second underground layer begins (m)
500.00	Thermal inertia of second underground layer (J.s-1/2.m-2.K-1)
1000000.00	Volumetric heat capacity of second underground layer (J.m-3.K-1)
F	Output (and compute accurately) soil temperatures (T:yes F:no)
0.8	Eps_front
0.85	Eps_back
0.813602015	Eps_G
5.67E-08	Sigma
0.25	**Efficiency assumed for computing the SA temperature**
0.91	Alpha
30.1	Solar Cell Area [cm2]

28	**SA Interface Operative Voltage (V)**
1	**Dust Deposit Factor (1= no attenuation)**
	Cosine Correction Factor
1	**Consider Corrective Factor Law (0/1)**
1	indice of refraction atmosphere
1.513	indice of refraction coverglass
	SA Electrical Network
13	**Nb cells per string**
500	SA internal harness resistance / string (mOhm)
	String Blocking Diode
2	n (0: no diode)
1.00E-10	saturation current (A)
	START COMPUTATION
24	**nb timesteps**

Figure 14-3: ESA flux tool input sheet

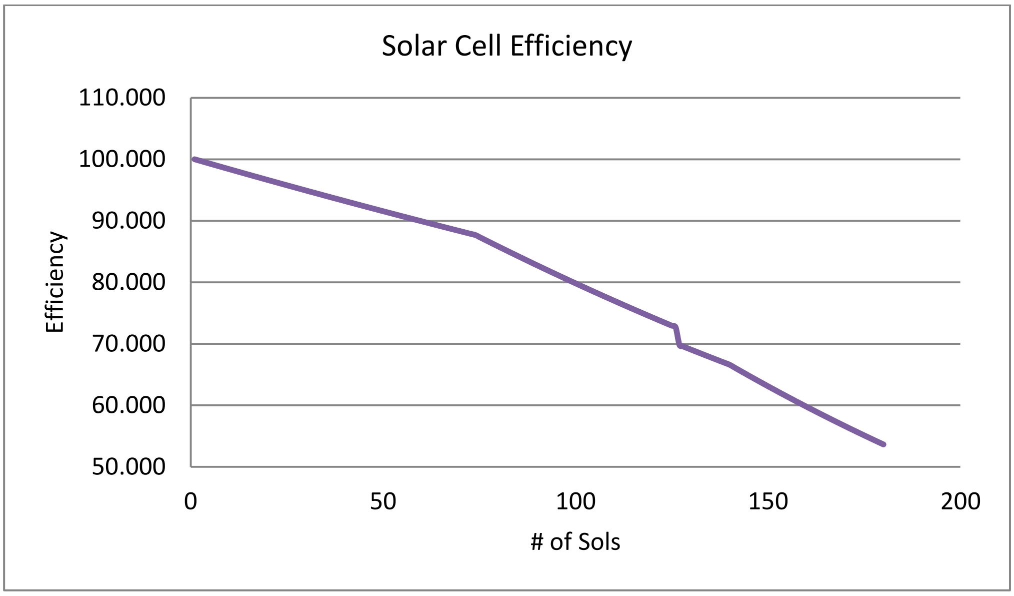

Figure 14-4: Pathfinder model: solar cells efficiency due to dust deposition vs. number of sols

LAT 20N has been considered for the sizing, being the worst case.

The system requirements are:

- Average 536 Wh/sol requested during sunlight (11hrs) (w/o margin)
- Average 272 Wh/sol requested during night (13hrs) (w/o margin)
- Considering the Wh/sol requested, the Power Conditioning and Distribution Unit (PCDU) architecture and 20% system margin, the total Wh/Sol required to be produced by the solar array is 1.090 kWh
- According to the dust deposition formula based on the Pathfinder model and the OD profile, the total loss after 110 sols is 23% (OD=1 and Ls=193) without any Dust removal system implemented
- 20% shadowing is also considered, due to the presence of the antenna
- 80% is considered as packing factor.

Total solar cells area needed is **1.8m²**, for a total panel area of **2.24m²**. Total mass is around **16 kg** included substrate.

The average Wh/Sol is around 607Wh/m² per Sol.

The efficiency of the solar cells has been computed supposing that the Maximum Power Point Tracker (MPPT) is working. A decrease of around 10% in average can be considered in case a DET (Direct Energy transfer) is operating at bus average voltage of 28V.

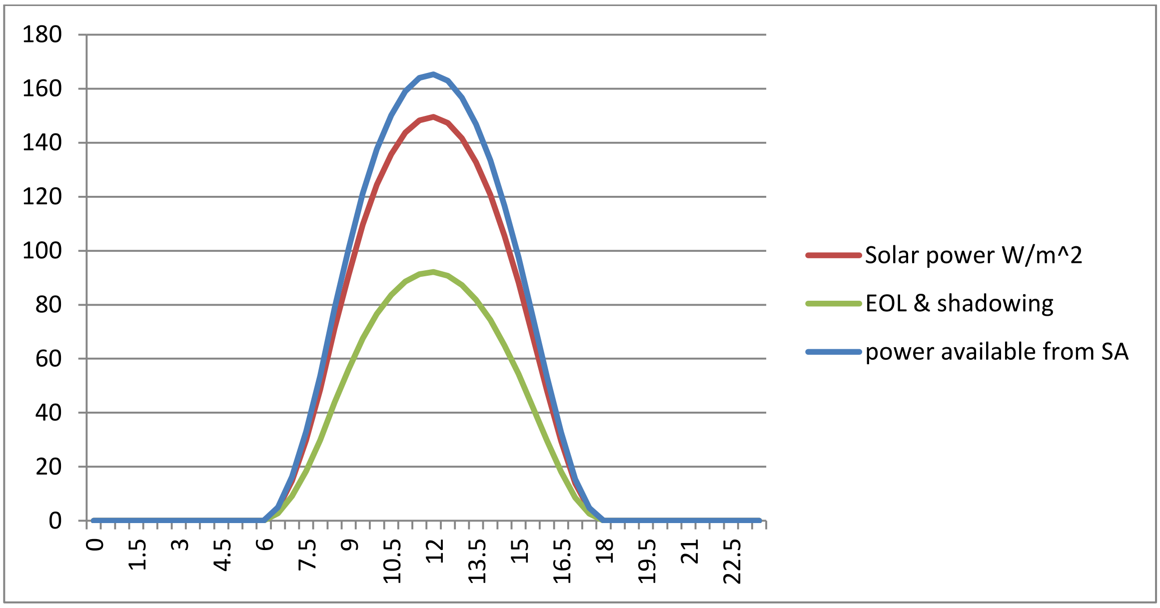

Figure 14-5: Solar cells Energy capability [W versus hrs]

The same solar cell area is able to produce:

- 464Wh per Sol at 246Ls, 20N LAT and OD=1.5 363Wh per Sol at 246Ls, 20N LAT and OD=2 482Wh per Sol at 193Ls, -5LAT and OD=1.5
- 1558Wh per Sol at 150Ls, 20NLAT and OD=0.5
- 1560Wh per Sol at 165Ls, 20NLAT and OD=0.5
- 1263Wh per Sol at 180Ls, 20NLAT and OD=1
- 1090Wh per Sol at 930Ls, 20NLAT and OD=1

The peak power generated at 36, 60 and 90 Sols of the mission timeline at N20 LAT are calculated (in bigger time steps) and summarised below.

Local Time	Power @ 36Sols (150Ls OD 0.5)[W]	Power @ 60Sols (165Ls OD 0.5) [W]	Power @ 90Sols (180Ls OD 1) [W]
0	0	0	0
2	0	0	0
4	0	0	0
6	5.14	2.46	0
8	99.62	96.79	66.26
10	183.74	187.09	157.87
12	211.22	215.74	189.16
14	179.14	182.65	152.77
16	95.78	93.03	65.339

Local Time	Power @ 36Sols (150Ls OD 0.5)[W]	Power @ 60Sols (165Ls OD 0.5) [W]	Power @ 90Sols (180Ls OD 1) [W]
18	4.81	2.26	0
20	0	0	0
22	0	0	0

Table 14-2: Power generation at 36, 60 and 90 Sols at LAT 20N.

Considering the 41W average power needed for locomotion and around 30W in Idle mode, it is possible to calculate for how many hours the rover can be traversed at specific mission periods.

- 1263Wh per Sol at 180Ls→347Wh more w.r.t. 110Sols during the day→390minutes TRAVERSE and 220min IDLE;
- 1560Wh per Sol at 165Ls→127Wh more w.r.t. 110Sols during the day→you can in theory TRAVERSE the whole time…

In case of the Contact Science Sol scenario, the solar cell area is not enough if science operation is requested at EOL of 180Sols.

In this scenario, as can be seen in the power budget,

- Average 364 Wh/sol requested during sunlight (10hrs) (w/o margin)
- Average 289 Wh/sol requested during night (14hrs) (w/o margin)
- Considering the Wh/sol requested and the PCDU architecture, the total Wh/Sol required to be produced by the solar array is 880Wh
- According to the dust deposition formula and the OD profile, the total loss after 180 sols is (OD=1.5 and Ls=246). 20% shadowing is also considered, due to the antenna and 80% packing factor.

Total solar cells area that would be need needed is **3.4m^2**.

The average Wh/Sol is around 258Wh/m^2 per Sol.

Mode		Thermal	Comms	DHS	Mech	GNC	StereoCam	HiResCam	CloseUp Cam	OSL	ATR	MeteoPack	Mössbauer	PCDU	TOTAL CONSUMPTION
Science Stop Short Mode	Pon	6.379001946	3	14			10	10				10		7	
	Pstdby	6.379001946	0	2											
4	Duty Cycle	100 %	100 %	100 %			13 %	17 %				100 %		100 %	
	Paverage	6.379001946	3	14			1.33	1.7				10		7	43 W
Tref 60 min	Total Wh	6.379001946	3	14			1.33	1.7				10		7	43 Wh
Science Stop Long Mode	Pon	6.379001946	3	14	60				8	12	3	6		7	
	Pstdby	6.379001946	0	2											
5	Duty Cycle	100 %	100 %	100 %	17 %				21 %	63 %	16 %	33 %		100 %	
	Paverage	6.379001946	3	14	10.2				1.68	7.5792	0.48	1.98		7	52 W
Tref 155 min	Total Wh	16.47908836	7.75	36.1667	26.35				4.34	19.5796	1.24	5.115		18.0833333	135 Wh
Science Stop Night Mode	Pon	12.15		14								6	4	4	
	Pstdby	12.15		2											
6	Duty Cycle	100 %		100 %								33 %	100 %	100 %	
	Paverage	12.15		14	0.02							1.98	4	4	36 W
Tref 60 min	Total Wh	12.15		14								1.98	4	4	36 Wh
Nominal Night Mode	Pon	12.15	26.4	14								6		4	
	Pstdby	12.15	1	2											
7	Duty Cycle	100 %	1 %	1 %								33 %		100 %	
	Paverage	12.15	0.2244	0.14								1.98		4	18 W
Tref 820 min	Total Wh	166.05	3.0668	1.91333								27.06		54.6666667	253 Wh
DTE Communications Mode Day	Pon	4.25	133	14 W	10							6		7	8
	Pstdby	4.25	14	2 W	0							0			0
8	Duty Cycle	100 %	0 %	100 %	3 %							33 %		100 %	100 %
	Paverage	4.25	0	14	0.33333333							1.98		7	28 W
Tref 30 min	Total Wh	2.125	0	7	0.1666667							0.99			10 Wh
Idle Mode Day	Pon	6.37	26.4	14								6		7	
	Pstdby	6.37	3.7	10											
9	Duty Cycle	100 %	1 %	5 %								33 %		100 %	
	Paverage	6.37	4 W	10 W								1.98		7	30 W
Tref 355 min	Total Wh	37.68916667	23.78333333	60.35								11.715		41.4166667	175 Wh

Figure 14-6: Contact Science Scenario power budget

14.3.2 Battery Sizing

Battery is 7s12p, at around 4.8 kg. It is considered that the battery SoC is 80% when entering the night and 30% min SoC has been taken as an assumption at the end of the night.

Harness efficiency		98%
PCDU losses		94%
battery efficiency		97%
cell type	18650 NL	
Wh needed during night	With 20% margin	326.4
SoC when entering night		80
Min SoC when going out night		30
Battery Wh needed	Wh	653
Battery fade during cruise		7
Battery Wh needed BOL	Wh	698
fade in 180 sols		5
numb cells		82
cells series		7
num strings		12
Total final Wh	Wh	754
mass	kg	4.8

Table 14-3: Battery sizing

14.3.3 Hibernation Sol

- In hibernation mode the system consumes 18W average (15W thermal system, 1W the PCDU and 2W DHU).
- The battery is sized to provide around 653Wh EOL.
- The average solar power available during the day at EOL (180 Sols and the occurrence of a local dust storm OD=2) is 363Wh.
- Considering day duration of 10hrs and night of 14Hrs, the battery is able to supply the system for around **12 nights** before being completely depleted.

		Thermal	Comms	DHS	PCDU	TOTAL CONSUMPTION
Hibernation Mode	Pon	14.56724137	0	0	1	
	Pstdby	14.56724137	0	0		
10	Duty Cycle	100 %	0 %	100 %	100 %	
	Paverage	14.56724137	0	0	1	16 W
Tref 0 min	Total Wh	0	0	0	0	0 Wh

Table 14-4: Hibernation mode power budget

14.3.4 EDL and Deployment Mode

In these two modes the power budget is shown in Table 14-4.

From the figure it is clear that the battery sized for the traverse sol scenario is not big enough to power the system in these two modes.

A bigger Li-Ion battery or a primary battery might be carried for powering the Rover until the first sunlight.

		Thermal	Loc s/s	DHS	PCDU	TOTAL CONSUMPTION
#1 EDL Mode	Pon	12.4561333		14 W	4	
	Pstdby	0		2 W	1	
	Duty Cycle	30 %		5 %	100 %	
	Paverage	4 W		3 W	4 W	20 W
Tref 2340 min	Total Wh	145.73676		102 Wh	156	784 Wh
#2 Deployment Mode	Pon	6.37	32.7	14 W	7	
	Pstdby	0		2 W	0	
	Duty Cycle	100 %		100 %	100 %	
	Paverage	6 W		14 W	7 W	42 W
Tref 600 min	Total Wh	63.7	4 Wh	140 Wh	70	421 Wh

Table 14-5: EDL and deployment mode power budget

14.4 Power System Mass (Including Margin)

Element 1	Rover		MASS [kg]				
Unit	Unit Name Click on button above to insert new unit	Quantity	Mass per quantity excl. margin	Maturity Level	Margin		Total Mass incl. margin
1	Solar Array	1	16.0	To be developed	20		19.2
2	Battery	1	4.7	To be developed	20		5.6
3	PCDU	1	7.0	To be developed	20		8.4
-	Click on button below to insert new unit		0.0	To be developed	20		0.0
SUBSYSTEM TOTAL		3	27.7		20.0		33.2

Table 14-6: Equipment mass budget

14.5 Technology Requirements

The following technologies are required or would be beneficial to this domain:

Equipment and Text Reference	Technology	Suppliers and TRL Level	Technology from Non-Space Sectors	Additional Information
Solar Cell	3G33	N/A		TRP activity (C. Baur)
Low temperature Li-Ion cells	Li-Ion cells	ABSL, TRL5		Expected follow-up to reach TRL 7
Regenerative Energy Storage System	High temperature fuel cell	Cmr, Prototech		ESA STRIN activity (Max
Solar Power Regulator Breadboard for Mars Surface Missions	PCU	N/A		TRP activity MREP (G. Simonelli)

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15 TELECOMMUNICATIONS

15.1 Requirements and Design Drivers

15.1.1 Requirements

The communications subsystem shall meet the following requirements:

Subsystem requirements		
Req. ID	**STATEMENT**	**Parent ID**
COM-010	The rover shall have the ability to receive Direct-from-Earth telecommands every sol	
COM-020	The rover shall be able to downlink 200Mbit of scientific and housekeeping telemetry data per sol	
COM-030	The rover shall be able to downlink Direct-to-Earth a minimum data volume of ~1Mbit	
COM-050	The link budget margins shall be as per ECSS standards defined in RD[35].	
COM-060	The use of ESA ESTRACK 35m ground stations (G/S) for a direct Mars-Earth link shall be considered	
COM-070	The rover shall be able to communicate to an existing orbiting asset during the nominal mission using a CCSDS Proximity-1 link in UHF	

15.1.2 Design Drivers

Based on the mission and subsystem requirements, the following design drivers have been identified:

- Based on the tight mission mass, power and volume constraints, the communication system is also severely limited in:
  - Volume
  - Mass
  - Power & energy
- COM-080 increases the impact of the previous driver as two transponders, high-power amplifiers (HPA) and electric power conditioners (EPC) are needed
- COM-030 combined with large distance between Mars and Earth during the mission set a lower limit the rover's DTE Effective Isotropic Radiated Power (EIRP)
- COM-020 drives the requirements imposed on:
  - The relay asset's orbit
  - The relay asset's return link G/T and therefore the relay's rover-facing antenna and receiver sensitivity
  - The EIRP of the rover's relay communication system.

15.2 Assumptions and Trade-Offs

15.2.1 Assumptions

In order to be able to perform any calculations, the following assumptions have been made.

15.2.1.1 Entry, Descent and Landing Phase

No communication is needed during EDL-Phase as the rover is landed on a pallet by NASA's EDL system.

15.2.1.2 Link geometry

- Direct to- and from- Earth communication shall be possible at a maximal distance of 2.6AU. This assumption was derived from the worst case distance in Figure 4-1. Only the three first launch dates were considered
  - October 2024-September 2025
  - November 2026-September-2027
  - December 2028-October 2029)
- The minimum viable elevation for DTE/DFE communication on RD[35]:
  - Earth is 5°
  - Mars is 10°.
- No communication can take place during solar conjuncture.

15.2.1.3 Relay asset

The relay asset considered is one similar to ESA's ExoMars Trace Gas Orbiter RD[40]:

- ~400km circular orbit
- 74° inclination
- UHF
  - Dual-string Electra UHF transceiver
  - Helical UHF LGA
- X-/Ka-Band
  - 2 x X-Band Transponder
  - 2 x Ka-Band Transponder
  - 2.2m X-/Ka-HGA with 2DoF pointing mechanism

15.2.1.4 Redundancy

Both the near real-time and the relay link shall exhibit hot redundancy for the receive function and cold redundancy for the transmit function.

15.2.1.5 Ground Segment

A constant implementation loss of 0.9dB at the 35m ESTRACK G/S for DTE communication is assumed based on best engineering estimations derived from preliminary internal investigations. The currently listed figure for the implementation loss at the considered symbol rate is 2.7dB but this value can be lowered with a delta development.

15.3 Trade-Offs

15.3.1 Communication Strategy

Relayed communications between Earth and a Mars rover using an orbiting asset has high potential delay because of the infrequent and short communication windows between rover and orbiter. This makes a store and forward scheme necessary and thus causes high data delivery delays.

Since both near-real-time and non-real-time communications are needed and the total data-volume (telemetry and Science data) is too high for DTE downlink, both a direct and a relayed communication link are needed.

Figure 15-1 shows the trade-off between antenna diameter and RF-power needed that would result in an EIRP of 56dBW. This equivalent radiated power is needed to downlink the 200Mbit (as a reference 120Mbits/sol short science mode including compression + 80 Mbits/sol rover housekeeping TM allocation) in 90min, resulting in a bitrate of 37kbit/s. As can be seen from the figure, the needed power never falls below 200W even for prohibitively large antenna diameters. This fact rules out the option of downlinking the entire 200Mbit/sol of data volume via an X-Band DTE link and makes it necessary to have an orbiting asset relaying the bulk of the data back to Earth.

In order to assess the proportion between direct and relayed telemetry data volume, an analysis was conducted based on the range between rover and the ground station. For this analysis, a 0.35m high gain dish antenna with 60% efficiency and 65W RF power at the output of the power amplifier were assumed; furthermore one of ESA's ESTRACK 35m stations was assumed as G/S as specified in COM-060. Figure 15-2 summarises the results of this analysis. The curve indicating the data volume to be relayed never drops below zero during the whole nominal mission which means that there is always a need to use the orbiting asset during the whole mission even when using the relatively high RF power of 65W.

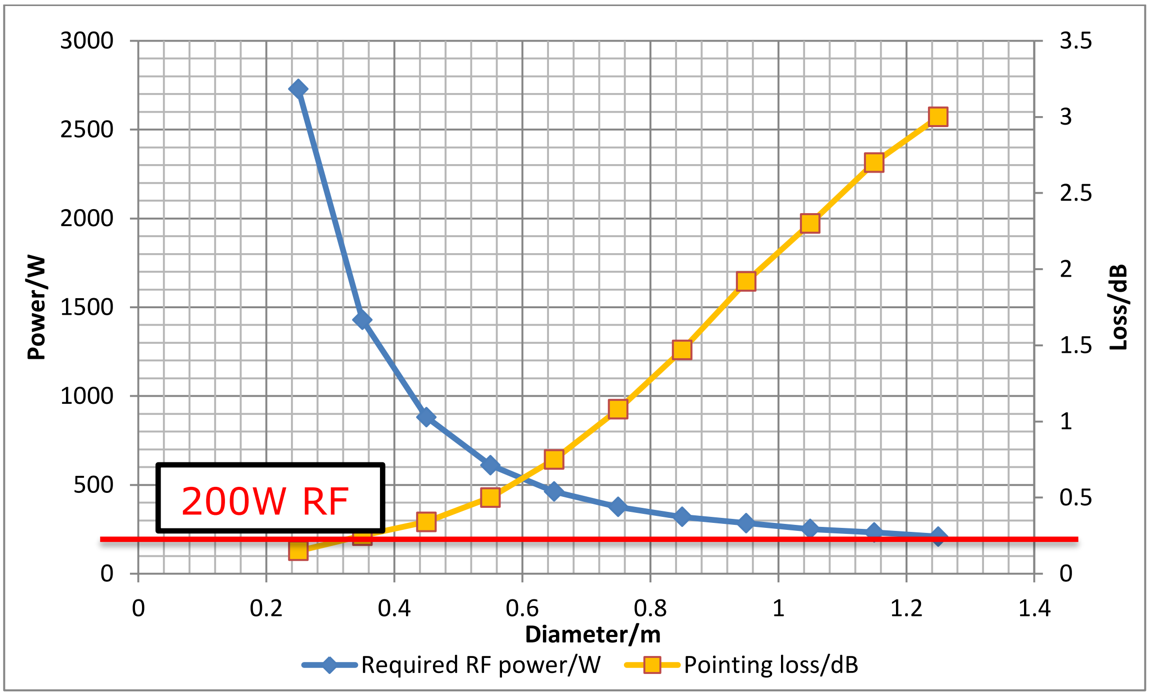

Figure 15-1: Required RF power vs. antenna diameter for 2° boresight pointing offset (power is indicated in Watts and loss in dB)

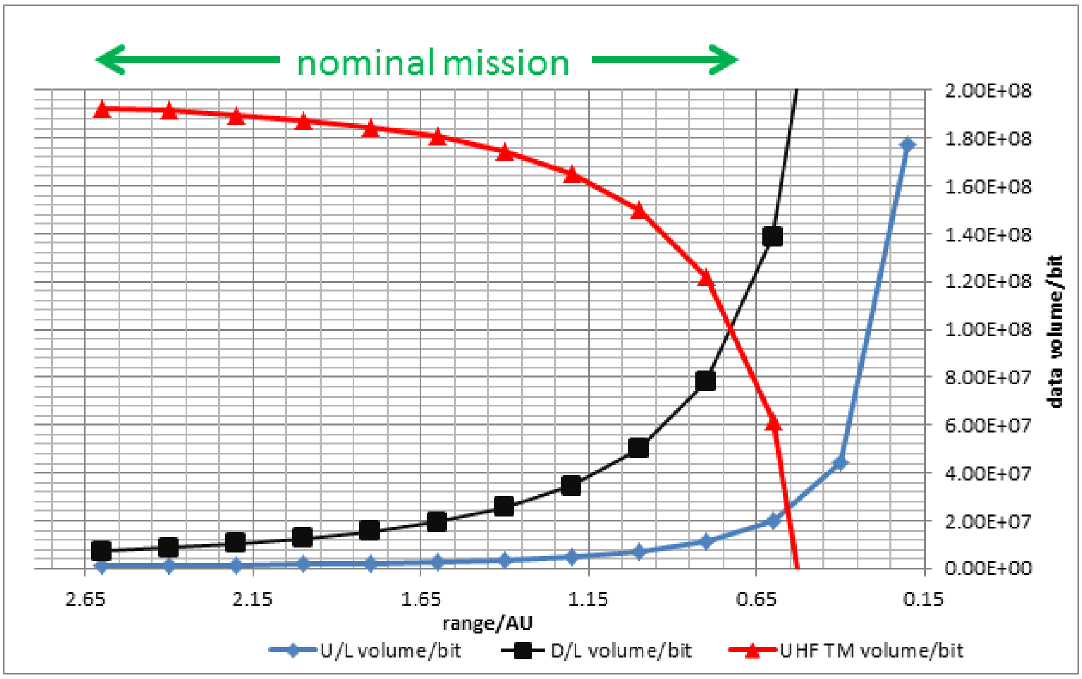

Figure 15-2: Proportion of direct and relayed telemetry vs. range (volume is indicated in bit and range in AU)

15.3.1.1 Direct-to/from-Earth link

For deep-space (category B) missions, only the frequency bands listed in Table 15-1 are allowed by RD[35].

Band	Frequency Band (MHz)	Direction
S	2,110-2,120	Earth-Space
S	2,290-2,300	Space-Earth
X	7,145-7,190	Earth-Space
X	8,400-8,500	Space-Earth
Ka	31,800-32,300	Space-Earth
Ka	34,200-34,700	Earth-Space

Table 15-1: Allowed TT&C frequency bands for cat. B missions

Since S-Band is the lowest frequency of the three available bands, it needs the biggest antenna to reach the same gain compared to X- and Ka-Band. The ESTRACK G/S network will not support future deep-space missions in S-Band. These facts rule out the usage of S-Band for the direct link which needs very high gain.

Ka-Band on the other hand can theoretically allow a design with the smallest antenna. Unfortunately there are no transponders and power amplifiers available for the restricted mass and power budget. On top of this, Ka-Band also features high and fluctuating losses due to Earth's and Mars' atmosphere. Ka-Band additionally imposes more stringent pointing requirements due to smaller beam-widths.

In X-Band, the atmospheric losses are relatively low (~1dB for most G/S locations) and required antenna size is moderate. Fortunately, there are a few options for X-Band deep space transponders available.

15.3.1.2 Rover-to/from-relay orbiter link

The links between rover and relay orbiter link does not need to take into account the same restrictions as the direct link as its signals will be too faint to interfere with Earth-bound communications assets. Traditionally, Ultra High Frequency (UHF; 300MHz-3GHz) has been used for local Mars links. NASA has used UHF in its last Mars orbiter and rover missions and ESA's TGO will also be equipped with a UHF transponder. UHF has also been considered for many similar studies like Mars Sample Fetch Return (SFR) and MarsREX RD[9]. This choice is cemented by the standardisation of UHF as the only supported band for the Proximity-1 protocol stack (the standard leaves the possibility for other frequency bands open though) RD[35]. Since there is no need to use another frequency, sticking to well proven designs is the best option.

15.3.2 Bandwidth trade-offs

Since MarsFAST is a deep-space (category B) mission, no absolute limits on bandwidth are imposed by RD[35].

The DTE telemetry link has a restriction on bandwidth of either:

- 1.1 x Symbol Rate, for 8,025MHz-8,400MHz
- Between 4MHz and 8MHz depending on symbol rate, for 8,400MHz-8,450MHz

For the data rates considered, the DTE downlink occupied bandwidth is between 1MHz and 2.7MHz while having a symbol rate of maximally 154MSym/s which is well in the allowable range.

15.3.3 Transponder Trade-Offs

General constraints on the transponder used in MarsFAST are: low mass, low size, low power usage, if possible dual-band UHF/X-Band.

15.3.3.1 Overview of transponders used in similar studies

In order to find a suitable transponder for MarsFAST, a small selection of recent similar studies was analysed.

Mission	Study	Transponder
Sample Fetching Rover (SFR)	Astrium RD[39]	UHF only DUX
Sample Fetching Rover (SFR)	TAS RD[40]	UHF only DUX
Mars Network Science Mission (MNSM)	ESA-CDF	DUX like
Mars Network Science Mission (MNSM)	TAS	DUX
Mars Network Science Mission (MNSM)	Astrium	DUX
Nasa Curiosity rover		Electra-Lite & Group III small deep space transponder RD[38]

Table 15-2: Transponders in similar missions

As can be seen from Table 15-2, all the listed missions either used the QinetiQ DUX in development as part of the ESA MREP technology plan, a variant of this transponder or a combination of Electra-Lite with some X-Band transponder.

15.3.3.2 Electra-Lite

NASA is using its Electra-Lite transponder for its latest Mars rover, Mars Science Laboratory/Curiosity. It has been derived from the “Electra Proximity Payload” a transponder first flown on Mars Reconnaissance Orbiter. Although this transponder was specifically designed to facilitate proximity links for Mars rover missions, it is not particularly suited for MarsFAST as it only supports UHF proximity communication. A second set of redundant X- or Ka-Band transponders would be needed to enable direct communications.

Projected specs from ~2003 RD[42]:

- Mass < 2.1kg
- Volume < 2200cm^2
- RF Power 10W
- Tx DC Power 40W
- Rx DC Power 10W

15.3.3.3 Lander Compact Dual UHF/X-Band Frequency Communications Package – DUX

Specs according to RD[37]:

- Mass 2kg
- Tx Power 23W
- Rx Power 1.5W (Wake on Hail)
- Size 180x100x50mm
- TRL 3

This transponder is potentially a very good fit for the MarsFAST mission. The required TRL 5 by 2018 should be achieved considering the implementation of the MREP-2 technology plan which aims at further developing this unit. . It fulfils all the major requirements, being light, small and power saving. The Wake on Hail mode is especially interesting since it would be active most of the time.. In this mission, the current built-in 5W transmitter in the X-Band chain would be of no use and should be removed such that an external power amplifier can be used with much higher output power.

15.3.4 Antenna Trade-Offs

Two types of antennae are needed, a high-gain antenna (HGA) for DTE/DFE communication and low-gain antennae (LGA) for relaying the bulk of the scientific and rest of telemetry data. In the following, the trade-offs for each type of antenna are explored.

15.3.4.1 High-gain antenna

The HGA needs to have a sufficient aperture to be able to generate the high gain needed for DTE communications. High aperture generally goes hand-in-hand with large dimensions. Due to power (small solar panels and battery) and space (small volume on palette and shading of solar panels) restrictions only relatively small antennae can be considered. In order to reduce the mass of the pointing mechanism, a very light antenna is necessary. To save volume and to facilitate accommodation in stowed configuration, a thin antenna is beneficial.

The classical design for a high gain antenna in X-Band is that of a parabolic reflector dish. Unfortunately, they are often quite heavy and need structure to support the feed.

An alternative to parabolic reflector dish antennae are metasurface antennae. They have many of the good properties of parabolic reflector dishes but with additional benefits and a few of the parabola's disadvantages missing. Metasurface antennae are very light and thin, they don't need a feed illuminating the antenna from its front side but have the feed embedded in the centre of the disc. They also provide a means to design the directivity pattern based on small metallic structures on their surfaces. This helps to decouple the physical design from the RF design and thus enables high flexibility in radiation pattern while keeping the physical envelope the same and keeping mechanical requirements stable.

15.3.4.2 Low-gain antenna

A great multitude of relative small form factor low gain antennas for UHF are available. Table 15-3 shows a comparison of different LGA designs taken into account for this study.

Model	Pattern	Mass	Size	Relia-bility	Cost	TRL	Other
Patch	+	0	-	0	0	5	Low BW
Solant	+	+	+	0	-	3	Low BW
Helix	+	-	-	0	0	8	
Monopole	-	+	+	+	+	8	-3dB pol.
Tilted monopole	0	+	+	+	+	8	-3dB pol.
Bent folded monopole	0	+	+	+	+	8 ExoMars	-3dB pol.

Table 15-3: Comparison of different Low Gain Antenna designs

The monopole and the bent folded monopole offers most advantages without knowing more about the relay satellite's orbit and communications capabilities. The final decision of LGA design must therefore be deferred until an orbiter has been determined.

15.4 Baseline Design

The following baseline design has been chosen based on the requirements of the mission. It tries to maximise the reliability while at the same time keeping mass and power usage low.

15.4.1 Architecture

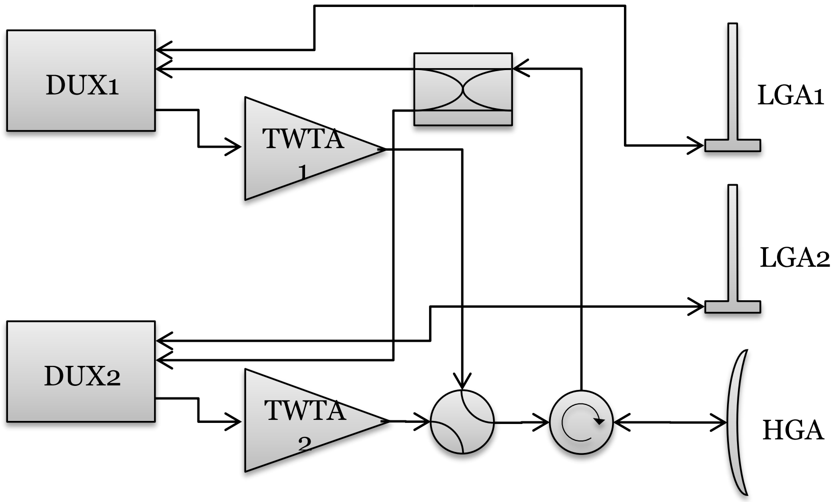

Figure 15-3: MarsFAST communications architecture block diagram

15.5 List of Equipment

The list of equipment used by the communications subsystem is given in Table 15-4.

Amount	Equipment	Comment
2	Modified **D**ual **UHF**/**X**-Band Transponder	Modified DUX with removed internal 5W X-Band amplifier
2	Traveling Wave Tube	65W RF output power
2	Electric Power Conditioner	90% efficiency
2	Low Gain Antenna	λ/4 monopole
1	High Gain Antenna	35cm diameter metasurface
1	RF distribution unit/network	

Table 15-4: Equipment

In the following, each item in the equipment list is described in more detail.

15.5.1 Modified Dual UHF/X-Band Transponder

The Dual UHF/X-Band Transponder DUX was developed by QinetiQ for ESA RD[37]. QinetiQ has already acquired expertise in building transponders for the Beagle-2, MarsExpress and ExoMars missions. The goal of the DUX development was to provide an integrated UHF/X-Band transponder for small deep-space missions.

The required TRL 5 by 2018 should be achieved considering the implementation of the MREP-2 technology plan which aims at further developing this unit.

Figure 15-4: Dual UHF/X-Band Transponder

15.5.2 Traveling Wave Tube Amplifier (TWT & EPC)

Figure 15-5 shows a typical TWTA consisting of a Traveling Wave Tube and its Electric Power Conditioner. These devices have a lot of heritage and are currently at TRL9.

Figure 15-5: Travelling Wave Tube Amplifier

The relevant parameters of this assembly are:

- RF output power: 65W
- TWT Efficiency: 60%
- EPC Efficiency: 90%
- Total consumed power (TWT + EPC): 108W + 11W = 119W

15.5.3 UHF Low Gain Antenna

The current baseline design uses monopoles as UHF relay antenna. They are of simple design and have a good heritage. Two drawbacks are their radiation pattern which has no power in zenith direction (cf. Figure 15-7) and 3dB loss due to linear polarization.

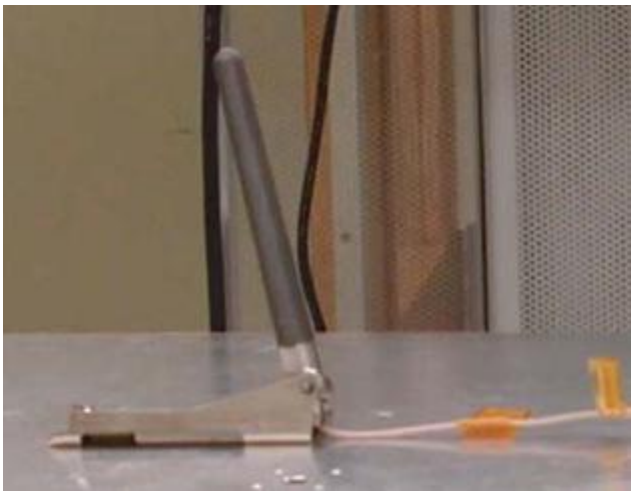

Figure 15-6: UHF Monopole

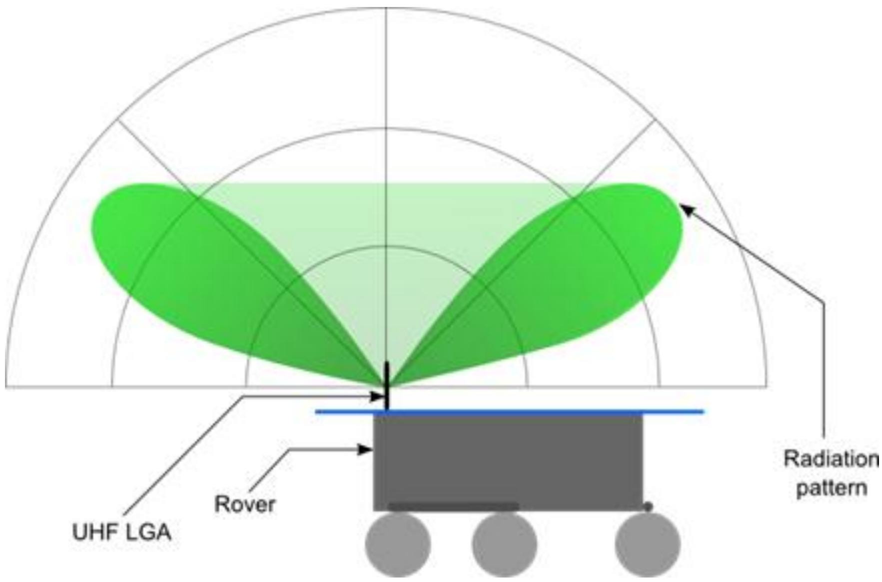

Figure 15-7: Qualitative UHF monopole radiation pattern

15.5.4 X-Band High Gain Antenna

A metasurface (cf. Figure 15-8) HGA was chosen as a baseline assuming a pointing error of 1° for the X-Band DTE/DFE link. It's lighter, thinner and less bulky than a regular parabolic reflector dish antenna and thus ideally suited for the MarsFAST rover. Since accommodation was problematic on the rover's top, it was decided to place the HGA on the main camera masts movable camera assembly. This makes it possible to save the space and mass of a separate pointing mechanism. The thickness of only ~3cm allows it to be stowed easily.

The metasurface HGA is made from a sandwich of a printed circuit board glued to a honeycomb that provides the necessary stiffness. The feed elements are inserted from the back and only measures a few millimetres (cf. Figure 15-8).

Table 15-5 summarises the main parameters for the HGA:

Parameter	Value
Diameter	0.35m
Efficiency	60%
Forward link frequency	7.145GHz
Max. forward link gain	26.14dBi
Gain - pointing loss @ 1° offset	26.14dBi-0.2dB = 25.94dBi
Return link frequency	8.4GHz
Max. return link gain	27dBi
Gain - pointing loss @ 1° offset	27dBi-0.3dB = 26.7dBi

Table 15-5: X-Band HGA Parameters

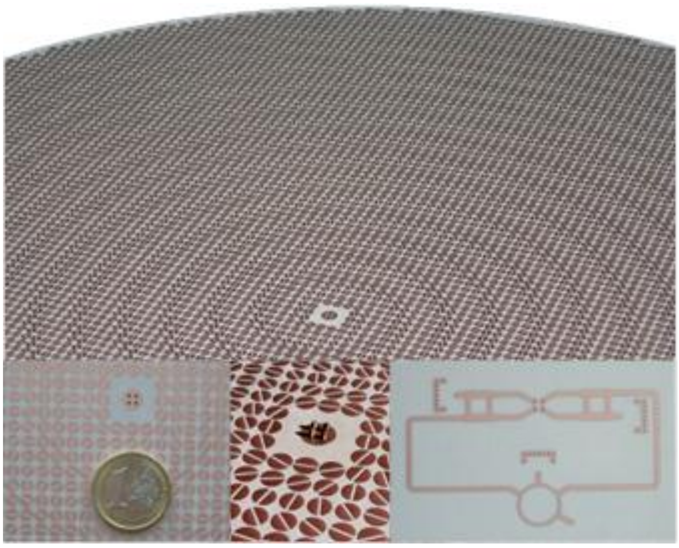

Figure 15-8: Metasurface High Gain Antenna with detail on feed and matching network

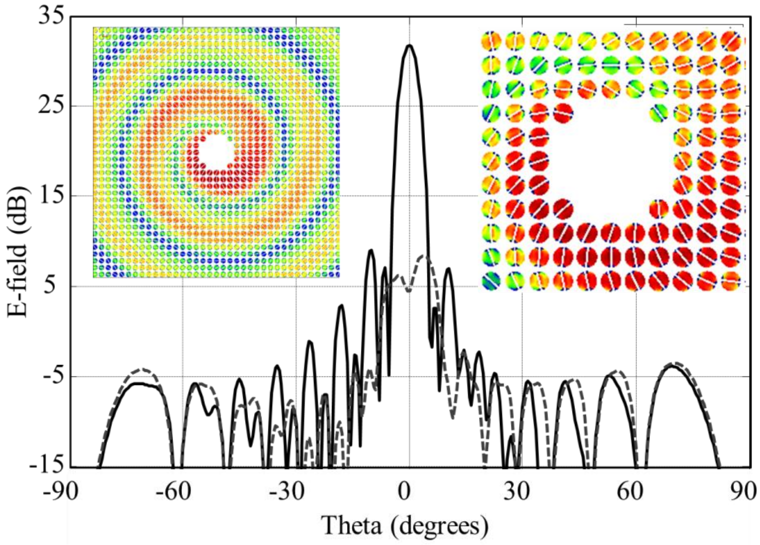

Figure 15-9: Example metasurface HGA pattern

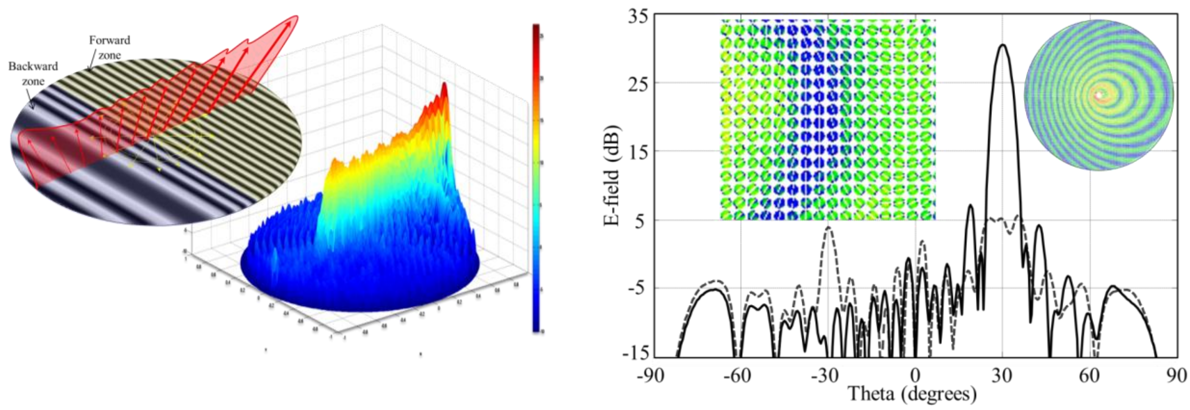

Figure 15-10: Example of a shaped pattern

15.5.5 Radio Frequency Distribution Unit

The Radio Frequency Distribution Unit (RFDU) is in charge of interconnecting the active modules (transponders and TWTA's) and the antennas. The RFDU is in charge of selecting the transmitting transponder and TWTA for X-Band DTE by means of the RF switch. Finally, it contains the RF diplexer that split uplink and downlink signals.

The proposed equipment has a current TRL of 9. Its mass is around 2 kg but subject to change as the architecture is not set in stone. Figure 15-11 shows an example RFDU (the depicted RFDU is more complex than the one needed for MarsFAST).

Figure 15-11: Example Radio Frequency Distribution Unit

15.6 Options

No options have been considered for the communications subsystem for this study.

15.7 Budgets

15.7.1 Link Budgets

In the following sections, the link budgets for both the direct and the relay link are presented. They are calculated in accordance to requirement COM-050.

Additionally, the following assumptions were made:

- X-Band residual carrier modulation index: 60° = 1.05 rad RD[37]
- Modulation scheme for direct link: PCM-NRZ/PSK/PM on square subcarrier
- Tx frequency band: 8.4-8.45GHz

15.7.1.1 Direct X-Band link

Since the range varies greatly during the nominal mission between around 2.6AU and 0.6AU, the direct link budgets have been calculated for different distances in that range.

The ground station taken into consideration for the direct link is one of ESA's 35m stations; they are the most powerful stations readily available for ESA missions:

- New Norcia, Australia
- Cebreros, Spain
- Malargüe, Argentina

With figures of merit in line with the following values:

- EIRP: 107.07dBi
- G/T: 49.91dB/K

The rover's direct communication system features an antenna as described in 15.5.4 Table 15-5. The link budget takes into consideration a pointing offset of ±1°.

15.7.1.1.1 Rover→Earth-Downlink

The modulation and coding schemes chosen are:

- Modulation: PCM-NRZ/BPSK(SQUARE)/PM
- Coding: Turbo Code 1/6.

They result in the following performance figures:

- Bit error rate: $1 \cdot 10^{-5}$
- Required $\frac{E_b}{N_0}$ for demodulation: -0.13dB

The results of the different downlink budgets are summarised in Table 15-6.

Range	2.6AU	2.4AU	2.0AU	1.4AU	1.0AU	0.6AU
Carrier rec. margin	13.3dB	14dB	15.58dB	18.68dB	21.6dB	26.4dB
TM rec. margin	3dB	3dB	3dB	3dB	3dB	3dB
Inform. rate / kbit/s	1.367	1.605	2.311	4.715	9.242	25.671
Time D/L 5Mbit / min	61	52	36	18	9	3
Time D/L 10Mbit / min	122	104	72	35	18	6
Time D/L 20Mbit / min	244	208	144	71	36	13
D/L Vol. 5min / Mbit	0.41	0.48	0.69	1.41	2.77	7.70
D/L Vol. 10min/Mbit	0.82	0.96	1.39	2.83	5.55	15.4
D/L Vol. 20min/Mbit	1.64	1.93	2.77	5.66	11.09	30.81
D/L Vol. 30min/Mbit	2.46	2.88	4.17	8.49	16.65	46.2
D/L Vol. 35min/Mbit	2.87	3.36	4.83	9.87	19.39	53.9

Table 15-6: X-Band direct telemetry link budget

15.7.1.2 Relay link

Table 15-7 summarises the assumptions taken for the preliminary UHF link-budget. It also indicates the resulting maximum possible raw bitrates under the taken assumptions for two elevation scenarios. The gain values of the rover's monopole antennae are idealized values and will probably be a few dB lower for a real system.

It can be seen that the forward link supports bitrates of up-to 64kbit/s and the return link supports bitrates between 256kbit/s and 2Mbit/s depending on the elevation. These rates allow the rover to uplink at least 80Mbit and downlink around 19Mbit per 5min communications time.

	Fwd. link: orbiter->rover		Ret. link: rover->orbiter	
	Near Nadir	Near Horizon	Near Nadir	Near Horizon
Frequency	4.36E+08		4.04E+08	
Modulation	*SP-L/PM*		*SP-L/PM*	
Mod. Index	*60°*		*60°*	
Coding	*None*		*Convolutional (2, 1, 7)*	
Transmit	**Orbiter**		**Rover**	
Tx Power/W	5		5	
Circuit loss/dB	2		1	
Offset to nadir/°	30	60	56.03	14.55
Gain Tx/dBi	5	1	-2.27	4.88
EIRP/dBW	8	4	1.73	8.88
Link				
Altitude/m	4.00E+05			
Mars radius/m	3.40E+06			
Elev. of orb./°	56.03	14.55	30.00	60.00
Range/m	4.71E+05	1.05E+06	7.02E+05	4.54E+05
Pol. loss/dB	3		3	
Prop. loss/dB	141.69	145.61	144.51	137.72
Receive	**Rover**		**Orbiter**	
Offset to ant. bore. / °	56.03	14.55	30.00	60.00
Gain Rx/dBi	-2.27	4.88	5	1
Circuit loss/dB	1		2	
Power at Rx/dBW	-135.96	-136.73	-137.78	-127.84
Acquis. thres./**dBW**	-160		-163	
Acquis. margin/dB	**24.04**	**23.27**	**25.22**	**35.16**
Data recovery	**Rover**		**Orbiter**	
Ant. Noise temp/K	100		200	
Noise figure/dB	3.4		2	
Total noise temp/K	448.70		476.64	
Received S/No / dBHz	66.12	65.35	64.04	73.98
Mod. losses / dB	1.25			
Impl. loss / dB	1.5			
Inform. Rate/ bit/s	64,000	64,000	256,000	2,048,000
Eb/No at Rx / dB	15.30	14.54	8.46	9.37
Required Eb/No / dB	9.6		4.9	
Demod. margin / dB	**5.70**	**4.94**	**3.56**	**4.47**

Table 15-7: Relay Link

15.7.2 Mass Budget

Table 15-8 shows the mass per unit and total masses of each unit being part of the communications subsystem.

Element 1	Rover			MASS [kg]			
Unit	Unit Name Click on button above to insert new unit	Part of custom subsystem	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
1	DUX		2.00	1.70	To be developed	20	4.1
2	TWT		2.00	1.00	Fully developed	5	2.1
3	EPC		2.00	1.50	Fully developed	5	3.2
4	HGA		1.00	1.00	To be modified	20	1.2
5	LGA		2.00	0.40	Fully developed	5	0.8
6	RFDU		1.00	2.00	Fully developed	10	2.2
-							
SUBSYSTEM TOTAL			6	12.2		11.2	13.6

Table 15-8: Communications subsystem mass budget

15.7.3 Power Budget

In the following tables, the power usage of the DUX transponder is shown in detail followed by a table aggregating the power usage by mode.

Power / W	Symbol	Base / W	Margin / %	Total / W
Baseband (partial)	P_{BB}	0.1	10	0.1
Baseband (Rx only)	P_{BBRx}	2.3	10	2.5
Baseband (full rate Tx + Rx)	P_{BBTx}	6.0	10	6.6
UHF Receiver	$P_{Rx,UHF}$	1.0	20	1.2
UHF Transmitter	$P_{Tx,UHF}$	17.8	5	18.7
UHF Wake on Hail	$P_{WoH,UHF} = P_{BB} + P_{Rx,UHF}$	1.1		1.5
Baseband + UHF Rx	$P_{BB+Rx,UHF} = P_{BBRx,UHF} + P_{Rx,UHF}$	3.3		3.7
Baseband + UHF Rx + UHF Tx	$P_{BB+Rx,UHF+Tx,UFH} = P_{BBTx} + P_{Rx,UHF} + P_{Tx,UHF}$	24.8		26.4
X Receive	$P_{Rx,X}$	1.5	20	1.8
X TWT	P_{TWT}	108.3	0	108.3
X EPC	P_{EPC}	10.8	0	10.8
X Modulataor	$P_{Mod,X}$	5.5	0	5.5
X Transmit	$P_{Tx,X} = P_{Mod,X} + P_{TWT} + P_{EPC}$	124.6		124.6

X WoH	$P_{WoH,X} = P_{BB} + P_{Rx,X}$	1.6		1.9
Baseband + X Rx	$P_{BB+Rx,X} = P_{BB} + P_{Rx,X}$	3.8		4.3
Baseband + X Rx + X Tx	$P_{BB+Rx,X+Tx,X} = P_{BB} + P_{Rx,X} + P_{Tx,X}$	65.2		69.8

Table 15-9: DUX Power usage details

System Operating Mode	Duty cycle	DUX1 status	DUX2 status	Required power/W
Traverse WoH, Hot redundancy	100%	UHF WoH (BB+Rx)	WoH	$2 \cdot P_{WoH,UHF} = 3$W
Traverse Rx+Tx	0%	Baseband + UHF Rx + UHF Tx	WoH	$P_{BB+Rx+Tx} + P_{WoH,UHF} = 27.9W$
Science Stop Short WoH	100%	UHF WoH (BB+Rx)	WoH	$2 \cdot P_{WoH,UHF} = 3$W
Science Stop Short Rx+Tx	0%	Baseband + UHF Rx + UHF Tx	WoH	$P_{BB+Rx+Tx} + P_{WoH} = 27.9W$
Science Stop Long WoH	100%	UHF WoH (BB+Rx)	WoH	$2 \cdot P_{WoH,UHF} = 3$W
Science Stop Long Rx+Tx	0%	Baseband + UHF Rx + UHF Tx	WoH	$P_{BB+Rx+Tx} + P_{WoH,UHF} = 27.9W$
Nominal Night Mode Tx	0.7%	Baseband + UHF Rx + UHF Tx	Off	$P_{BB+Rx+Tx} = 26.4W$
Nominal Night Mode WoH	99.3%	UHF WoH	Off	$P_{WoH,UHF} = 1.5W$
Communications Day Rx	25%	Baseband + X Rx	X WoH	$P_{BBRx} + P_{Rx,X} + P_{WoH,X} = 6.3W$
Communications Day Rx+Tx	75%	Baseband + X Rx + X Tx	X WoH	$P_{BBTx} + P_{Rx.X} + P_{Tx,X} + P_{WoH,X} = 135.2$

Table 15-10: Communications subsystem power usage by mode

Element 1 Unit	Rover Unit Name	Part of custom subsystem	Quantity	PPEAK AND POWER SPECIFICATION PER MODE PPEAK AND POWER SPECIFICATION PER MODE									PPEAK AND POWER SPECIFICATION PER MODE PPEAK AND POWER SPECIFICATION PER MODE								
				ROV_TRA	ROV_TRA	ROV_TRA	ROV_SSS	ROV_SSS	ROV_SSS	ROV_SSL	ROV_SSL	ROV_SSL	ROV_NOMN	ROV_NOMN	ROV_NOMN	ROV_COMD	ROV_COMD	ROV_COMD	ROV_IDLE	ROV_IDLE	ROV_IDLE
	Click on button above to insert new unit			Pon	Pstby	Dc	Pon	Pstby	Dc	Pon	Pstby	Dc	Pon	Pstby	Dc	Pon	Pstby	Dc	Pon	Pstby	Dc
1	DUX		2.00	3.0	27.9	100.0	3.0	27.9	100.0	3.0	27.9	100.0	26.4	1.5	0.7	6.3	16.0	25.0	27.9	3.0	1.4
2	TWT		2.00													0.0	108.3	25.0			
3	EPC		2.00													0.0	10.8	25.0			
4	HGA		1.00																		
5	LGA		2.00																		
6	RFDU		1.00																		
-													-								
SUBSYSTEM TOTAL			6	3.0	27.9		3.0	27.9		3.0	27.9		26.4	1.5		6.3	135.2		27.9	3.0	

Table 15-11: Communications subsystem power budget

15.8 Technology Requirements

The following technologies are required or would be beneficial to this domain:

Equipment and Text Reference	Technology	Suppliers and TRL Level	Technology from Non-Space Sectors	Additional Information
DUX	Removal of internal X-Band amplifier	TRL3		It is planned to be further **developed in the MREP-2 technology plan**
DUX	Removal of fixed modulation index for X-Band communication	TRL3		It is planned to be further developed in the MREP-2 technology plan
DUX	Remove capability to support entry-descent and landing phase from functional and operational requirements	TRL3		It is planned to be further developed in the MREP-2 technology plan
Metasurface HGA	Development of high power X-Band version qualified for Mars environment	**TRL3**		**No planned development for an X-band version under way**

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16 DATA HANDLING

16.1 Requirements and Design Drivers

SubSystem requirements		
Req. ID	**STATEMENT**	**Parent ID**
DH-010	The C&DH unit shall be able to perform the rover navigation and locomotion algorithms with the required performance	
DH-020	The C&DH unit shall include non-volatile mass memory storage	
DH-030	The C&DH unit shall interface the TT&C chains	
DH-040	The C&DH design shall minimise its mass and power consumption	
DH-050	The C&DH design shall provide high reliability with gradual performance degradation in case of failure	

16.2 Assumptions and Trade-Offs

The rover navigation and locomotion algorithm is really demanding in terms of performance. ESA TEC-MMA is leading several activities to implement those algorithms in a representative architecture. In order to meet the performance requirements, the implementation of those algorithms has been partitioned in SW and HW.

In the SEXTANT activity RD[43], the HW part of the algorithm has been implemented in a commercial XILINX XC6VLX240T-2 FPGA, with an internal resource utilisation of around 14% Slices, 10% LUTs, 57% of internal memory and 7% DSPs.

In the next step, the COMPASS activity will implement the algorithm in space qualified FPGAs. The target device is the NG-FPGA (MUSE), a high-capacity, high-performance, radiation hardened reprogrammable European FPGA manufactured in STM 65nm technology, with first "qualified" samples available in 2017. First resource utilisation estimations show that the algorithm would occupy around 3-4 of those devices, with a preliminary estimated power consumption of around 5-8W per device.

The preliminary estimated overall power consumption of the dedicated navigation processing HW would be around 25-30W, including the FPGA, oscillators, memories and the co-processor to run the SW part of the algorithm. This estimation could be refined once the devices are ready.

Anyhow, in order to comply with the power requirements for the subsystem, the power consumption of C&DH subsystem shall be reduced and several technology developments are needed:

- Navigation algorithms: Less optimal solutions, performance degradation, shared resources, simplification of the algorithms
- Low-power, high-performance FPGA technology: 28nm technology, low-power designs

- ASIC development for the navigation algorithms in low-power technology
- Low-power processors, based in architectures with better performance/power ratios such as ARM.

16.3 Baseline Design

The baseline design consists of a single, centralised unit implementing all C&DH functionality. The unit contains the following functional elements:

- Hot redundant power conversion module, on-board timer, safeguard memory, reconfiguration module and telecommand decoder
- Cold redundant processor module, IO modules, mass memory modules and telemetry encoders
- Non redundant navigation processing HW, consisting of a co-processor and a dedicated ASIC/FPGA.

The unit has the possibility to enter into hibernation mode, with extremely low power consumption. The unit is equipped with a non-volatile mass memory to maintain scientific and housekeeping data.

The OBC is based on highly integrated processors such as Airbus SCOC3 or Aeroflex Gaisler GR712. Those components provide plenty of IO capabilities, thus reducing the need for external programmable devices. For memory management, reconfiguration and any other missing functionality, the use of Flash-based low-power FPGAs such as Microsemi RTProasic is recommended, although some other non-ITAR alternatives may be identified.

The command and control bus of the rover may be based in CAN bus or any other low-power consumption bus. The use of point-to-point communication links, HPC, discrete digital IOs and similar interfaces has to be minimised in order to reduce the mass of the harness and connectors. If possible, scientific data and command and control messages must be routed through the same bus, assigning higher priority to those with strong real-time requirements.

The navigation processing HW may be based in a high performance co-processor and a dedicated ASIC or low-power FPGA performing the image processing algorithms. The baseline design does not foresee any HW redundancy for this functionality. In case of failure, the execution of these algorithms will be done in the main processor module, with an associated degradation in their performance.

The core is quite complex and it requires a lot of resources. In current, space qualified FPGA technology, that would imply the use of several devices and a power consumption not compliant with the mission requirements.

16.4 List of Equipment

The C&DH subsystem design consists of a single unit with the following parameters:

- Mass: 6.1 kg (incl. 10 % margin)
- Dimensions: 540X400x30 mm
- Power: Pon = 14W, Pnav = 25W, Pstby=2W

Element 1	Rover			MASS [kg]			
Unit	Unit Name Click on button above to insert new unit	Part of custom subsystem	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
1	RV OBC		1	5.5	To be modified	10	6.1
2					To be modified	10	0.0
-	Click on button below to insert new unit						
SUBSYSTEM TOTAL			1	5.5		10.0	6.1

Table 16-1: Equipment List and Mass Budget

16.5 Options

With the current technology, if mass and power budgets of the unit have to be further reduced, the redundancy scheme could be redefined, lowering the overall reliability of the C&DH subsystem.

In principle, it could be possible to have a non-redundant unit, that in case of SEU simply reboots the processor and waits for ground contact. In such a low radiation environment as the Martian surface the occurrence of those upset would not be frequent and the impact on the mission could be acceptable.

16.6 Technology Requirements

The following technologies are required or would be beneficial to this domain:

Included in this table are:

- Technologies to be (further) developed
- Technologies available within European non-space sector(s)
- Technologies identified as coming from outside ESA member states.

Equipment and Text Reference	Technology	Suppliers and TRL Level	Technology from Non-Space Sectors	Additional Information
C&DH	Low-power FPGA/ASIC	TRL 4	Yes	Technology widely available in non-space sectors

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17 THERMAL

17.1 Requirements and Design Drivers

17.1.1 Mission Requirements

The baseline mission scenario was to land between latitude -5° to 20° and to operate for 180 SOLs without RHU. There were no constraints on the longitude, therefore areas on Mars with low surface thermal inertia and high Albedo will have large temperature excursions which can be beyond the capabilities of existing and conceptual solar mission designs with RHUs. Therefore, it is required to limit the landing sites to areas between latitude -5° to 20° with a thermal inertia above 150, which is currently the baseline on Exomars. Otherwise, the energy consumption to maintain the units above their minimum operating temperature could be too high for the power sub-system.

17.1.2 Mars Environment

Similar to Earth, Mars undergoes seasonal changes in its weather pattern. The main contributor is the planet axis of 25° and the orbit eccentricity, which are causing repeatable sun angle and solar intensity fluctuation through one Martian year. Through surface and orbital measurements we see a distinct and repeatable pattern in the surface temperature, surface pressure and atmospheric. The surface pressure variation is caused by the migration of CO_2 from the South Pole to the North Pole and vice versa, which is governed by the sun angle and accentuated by the orbit eccentricity. The atmospheric opacity follows roughly the same pattern; however the range is very unpredictable due to the local and global dust storms. Nevertheless, depending on the mission arrival date, landing site, and mission duration, the thermal environment may differ significantly from mission to mission since the extremes of the environmental parameters do not occur at a specific location and time. Therefore, proper care in choosing the thermal environments must be considered in order to avoid over constraining the mission by choosing unrealistic sets or combinations of parameters that may not occur at the same time and location.

17.1.3 Specification of the Environmental Parameters

The Laboratoire de Météorologie Dynamique (LMD) in Paris, France, through a contract issued by ESA, developed a 1D atmospheric thermal tool that can predict the downward thermal infrared radiation, ground temperature and near surface air temperature as well as direct and diffuse solar flux onto an horizon flat plate. The modeling tool was derived from the existing 3D global climate model, where the results are publicly available through the Mars Climate Database11 (MCD). The LMD 1D flux tool is complementary to the MCD where key Martian environmental parameters can be inputted to generate engineering thermal design environments.

The input parameters are:

- Areocentric longitude, Ls
- Landing site latitude
- Ground pressure

- Atmospheric opacity
- Local surface Albedo
- Thermal inertia of near-surface ground layer
- Infrared emissivity of bare ground.

The thermal inertia and the surface Albedo have a significant influence on the surface temperature (see Figure 17-1). The surface pressure and atmospheric opacity have little influence. However, the atmospheric opacity has a large impact onto the apparent sky temperature or reflected infra-red flux, similar to the green-house effect. Clear nights, with low atmospheric opacity, have the lowest temperature since the rejection to deep space is at the maximum. Depending on the surface finish of the Rover, the effect of the sky temperature may drive the heater consumption during the night. High optical depth cases are generally not a sizing case for the thermal sub-system. However, due to the lack of solar electrical power, when used, indirectly impacts the thermal sub-system.

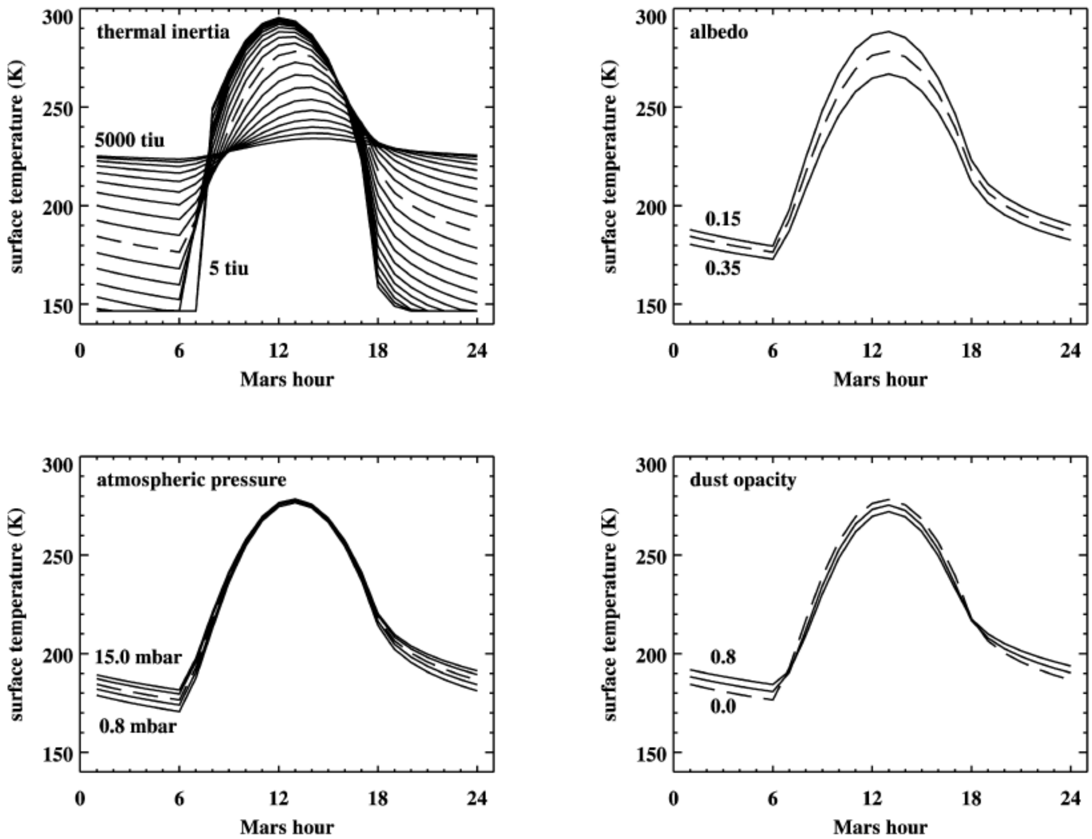

Figure 17-1: Effect of the Individual Parameters onto the Surface Temperature RD[47]

17.1.4 Design Driver

The Martian atmosphere has a very low pressure, 5 to 10 mBar. However, at those pressures, it is sufficient to have conduction through the CO2 gas as well as natural and force convection. Therefore, the insulation method is very similar to an Earth application where the thickness mainly drives the insulation efficiency. However, the advantages over the Earth environment is that due to the low pressure and reduced gravity, the natural convection will be trigger in much larger volume when compared to Earth. Hence, gaps and empty spaces smaller than 3cm around equipment can be used as insulation since the CO2 will remain still and it has a relatively low thermal conductivity.

The main contributor to the heat loss is through the insulation. Roughly, the heat loss from the insulation accounts for 2/3 of the overall heat loss. The remaining 1/3 would be through the support structure and harnesses. Therefore, the main challenge is to find the volume to accommodate a thick insulation, i.e. 3 cm to 10 cm.

The Rover bathtub external surfaces and solar arrays are exposed to the environment where the main contributor for heat exchange is the Solar heat input, Sky, wind and ground. Depending on the surface finish, one can reduce or increase the effect of each of those components except for the wind. The dust accumulation on the external surface will not have a significant role on the thermal control since the solar arrays have already a very high emissivity finish. Therefore the thermal coupling from the rover to the Sky will remain roughly the same throughout the surface mission regardless of the amount of dust accumulated on top. Vertical surfaces will not see significant dust accumulation, hence one can use low emissivity finish to increase solar input in the morning and evening while reducing the exchange with the ground.

17.2 Thermal Environment

The thermal inertia was constrained to a value of 150 and above based on ExoMars experience. Typically a cold case would have a low thermal inertia which would create a very cold temperature in the early hours of a sol. Several landing sites were selected and the thermal environment was determined using available data in the Mars Climate database and remote sensing information available through a java application called JMars.

There are six cases that were determined. Table 17-1 lists the landing site environmental parameters for cold operational cases including survival cases with global and regional dust storm. Two cold cases from Exomars are listed as reference. It is expected that in this type of environment, the Rover would have to operate nominally and would need to survive the dust storm cases. Table 17-2 lists the temperature extremes of the sky, ground and wind as well as the solar fluxes. The worst cold would be at Latitude -5 with a clear sky at Ls 140. However, the Exomars cold case at latitude -5 with clear sky is even colder.

Description	Optical Depth, τ	Surface Albedo	Ls	Pressure (Pa)	Thermal Inertia (J m-2 K-1 s-1/2)	Latitude, (oN)
Hot Case Latitude -5	0.5	0.15	258	660	210	-5
Hot Case Latitude 20	0.12	0.135	140	758	200	20
Cold Case Latitude 20	0.5	0.28	258	520	150	20
Cold Case Latitude -5	0.1	0.302	140	540	150	-5
Cold Case Latitude 20 Local Dust Storm	2	0.28	258	520	150	20
Cold Case Latitude 20 Gobal Dust Storm	5	0.28	258	520	150	20
Exomars Cold, Lat -5, Clear Skies	0.08	0.27	82	656	150	-5
Exomars Cold, Lat -5, Local Dust Storm	2	0.27	82	656	150	-5

Table 17-1: Landing Site Environment Parameters

		Sky Temperature			Ground Temperature			Wind Temperature		
Description	Solar Max	Min	Max	Average	Min	Max	Average	Min	Max	Average
Hot Case Latitude -5	621.26	-122.10	-89.43	-107.23	-82.31	31.33	-37.13	-78.00	-2.48	-45.23
Hot Case Latitude 20	550.36	-141.59	-114.81	-128.91	-91.14	21.28	-44.05	-86.35	-16.92	-53.47
Cold Case Latitude 20	451.61	-141.74	-114.70	-129.86	-108.01	-8.78	-71.83	-104.15	-35.55	-76.44
Cold Case Latitude -5	517.51	-157.40	-131.56	-145.65	-110.57	-2.09	-67.15	-106.19	-36.83	-74.57
Cold Case Latitude 20 Local Dust Storm	147.99	-117.00	-82.66	-101.52	-96.55	-23.87	-69.59	-93.93	-36.73	-71.76
Cold Case Latitude 20 Gobal Dust Storm	53.28	-100.62	-64.64	-84.14	-87.29	-44.97	-69.46	-86.07	-48.27	-70.13
Exomars Cold, Lat -5, Clear Skies	423.72	-160.97	-138.09	-150.50	-113.67	-14.42	-74.26	-109.53	-46.70	-80.68
Exomars Cold, Lat -5, Local Dust Storm	288.49	-115.36	-88.67	-103.15	-95.97	-27.24	-80.68	-93.20	-41.95	-72.58

Table 17-2: Maximum, Minimum and Average Temperature of the Environment

Figure 17-1 shows the solar fluxes expected on a horizontal flat plate for each case. Figure 17-2: to Figure 17-5: show the Sky, Ground and Wind temperature profile over one SOL expected on the Martian surface for each case.

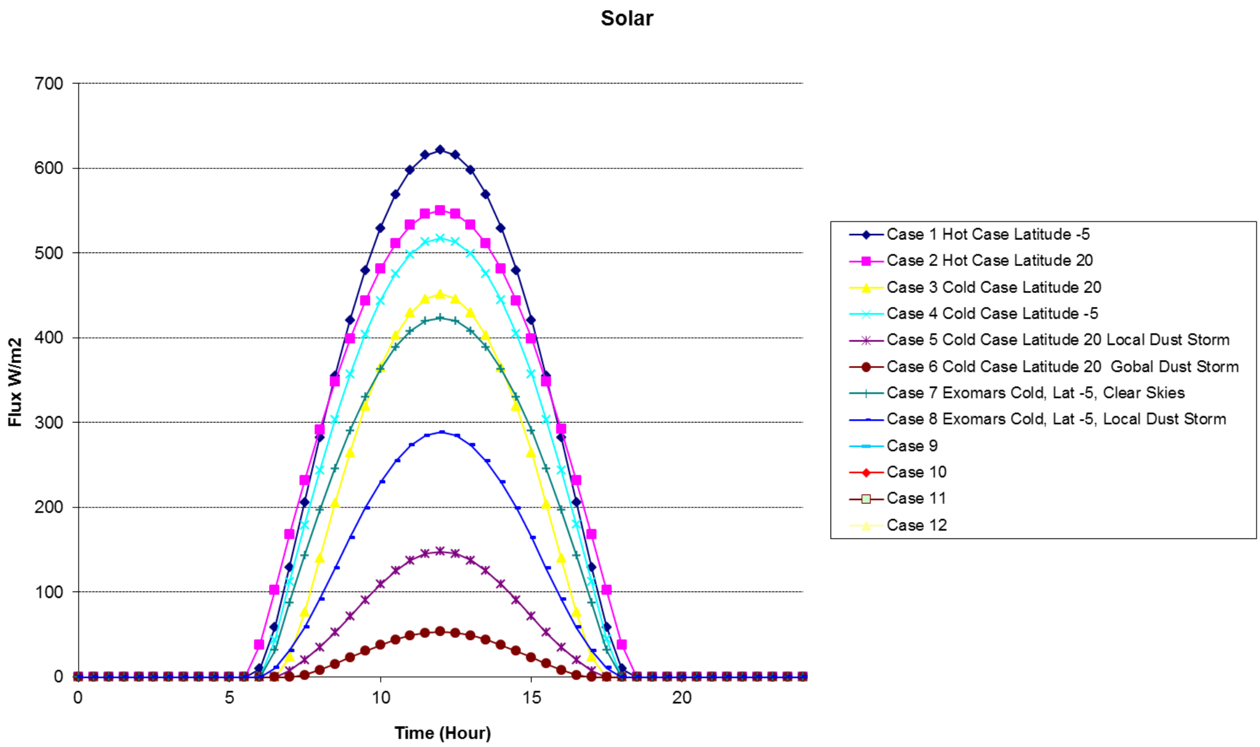

Figure 17-2: Total Solar Fluxes

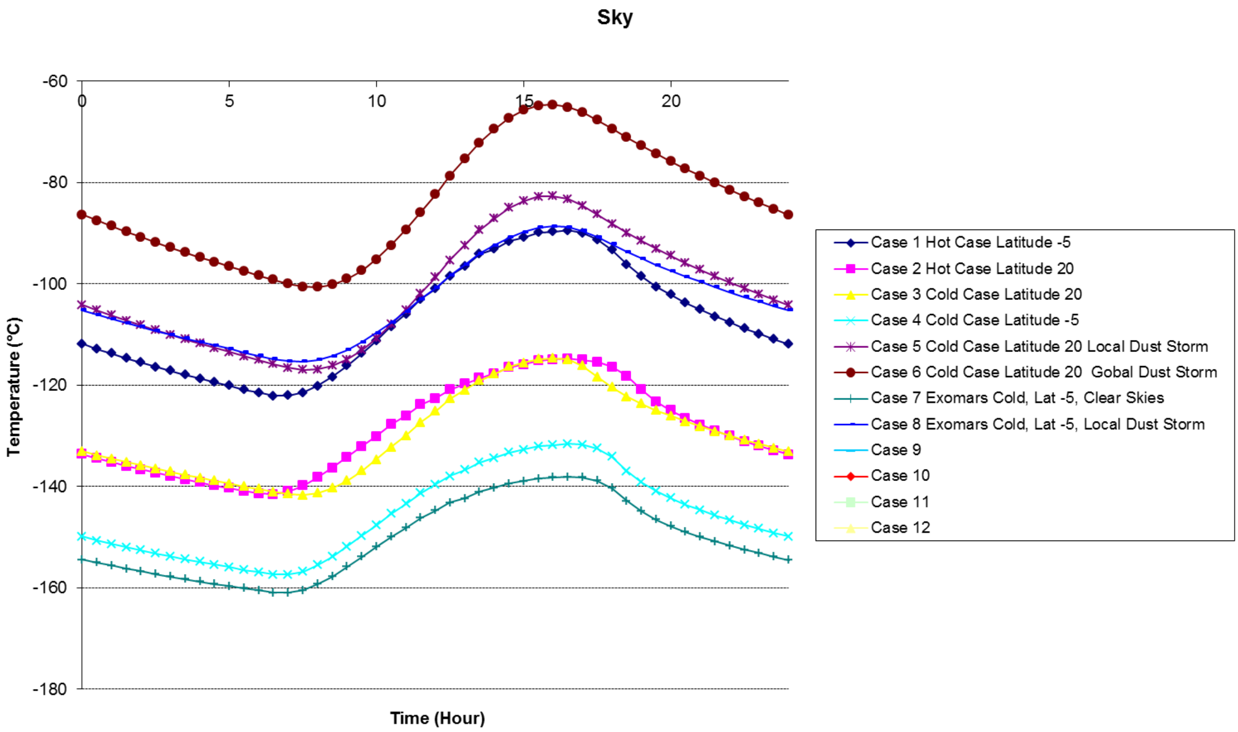

Figure 17-3: Sky Temperatures

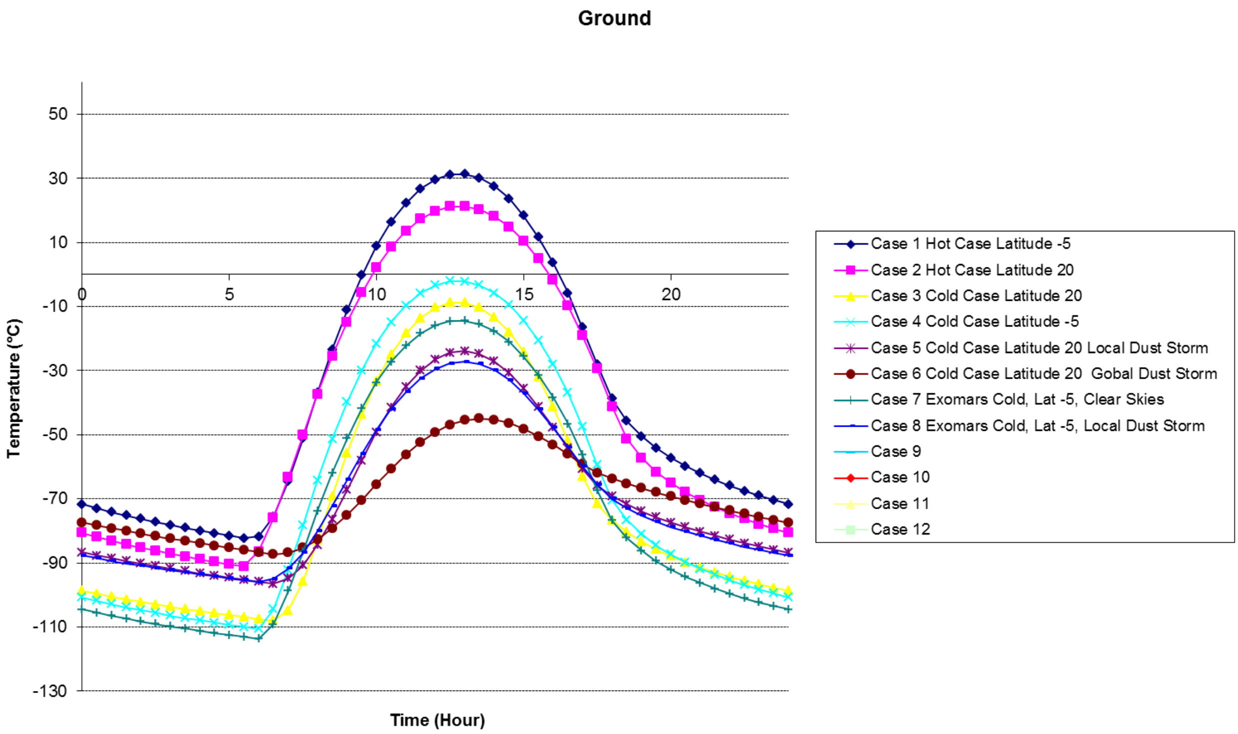

Figure 17-4: Ground Temperatures

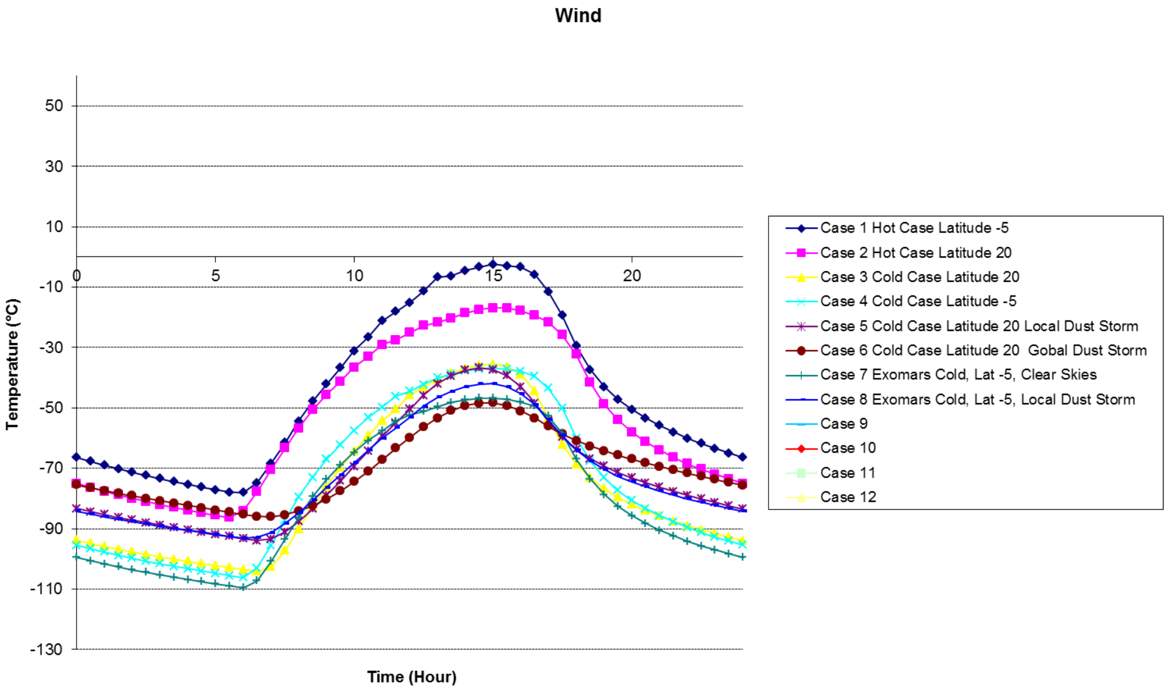

Figure 17-5: Wind Temperatures

17.3 Baseline Design

Past missions used fibre glass and foam type insulation. These types of insulations are very efficient but since they have relative higher density, their performance compared to CO2 gas conduction is slightly higher. The Pathfinder and MER Rovers used a rigid Aerogels insulation, which in theory, the thermal conductivity should be lower than CO2 due to the nano structure within the Areogel. However, Aerogels are fragile and require a supporting structure to prevent it from collapsing. The MSL rover uses a Gas-Gap insulation, which is essentially empty space between the external walls of the rover and the equipment. A 6cm gap is used to insulate the internal component. Baffles can be used to prevent the natural convection from occurring. This is a light weight approach compared to the Aerogel but slightly less efficient.

The baseline design would be to use an Aerogel insulation of 3 cm on the internal walls of the rover bathtub or as a backup the gas gap could be used instead, which is currently the baseline on Exomars. In addition, the Battery would need an additional blanket of 3cm thick since it is maintained at a higher temperature compare to electronic units. The battery would have 3cm high stand-off from the base plate.

The units will have a Common Plate with the minimum amount of support to the cold bathtub structure. It is assumed that 6 Stand-offs of 3 cm will be used and the material should be glass fiber. Low emissivity finish as “gold plated” will be used for the units and enclosure internal surfaces, which will reduce the heat loss through radiation.

Several Loop Heat Pipe (LHP) thermal switches will be used to remove excess heat during operations. The heat is conducted to the LHP evaporator, (Figure 17-6) where the working fluid evaporates, travels to the radiator where it condenses. A pressure sensitive valve regulates the flow within the LHP, which at a given evaporator temperature can stop the flow, stopping the heat flow to the outside. It is assumed that two LHPs will be dedicated to the service module (SVM) and would be accommodated as done in Exomars (see Figure 17-7). Another LHP would be allocated to the payload electronics. These types of LHPs have been tested in a TRP as well as in a breadboard in Exomars. The technology is being qualified within the frame of Exomars. The condenser or radiator total surface would need to be roughly 0.19 m^2.

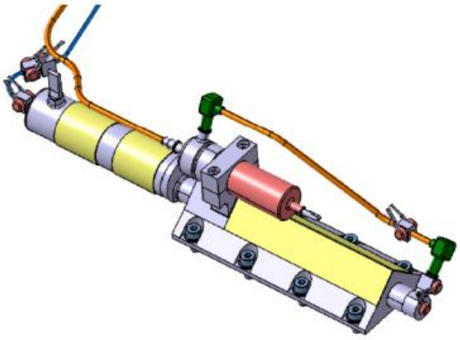

Figure 17-6: Exomars Loop Heat Pipe Evaporator

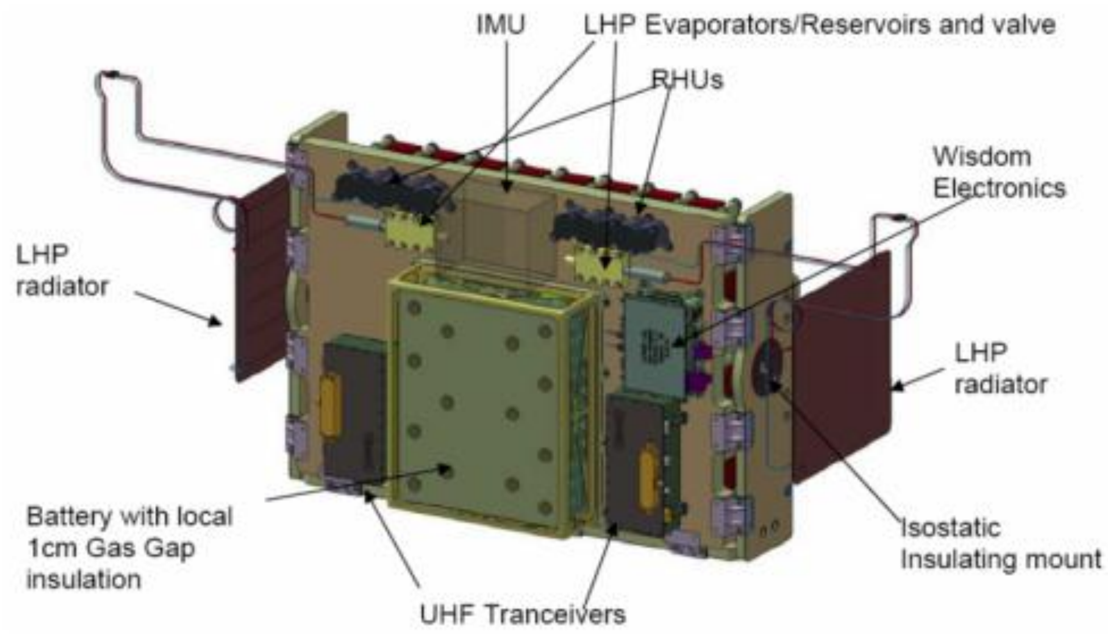

Figure 17-7: Loop Heat Pipes accommodation on Exomars SVM LHP

17.4 Predicted Heater Power

The heater power required to maintain the units within the allowable temperatures have been scaled based on the power predictions from Exomars. The heat loss of the rover is proportional to the surface area exposed to the environment. A 40% margin has been added to the calculated energy consumption values in order to account for model uncertainties. In addition, by using the energy consumption from Exomars and baselining the use of aerogel instead of the less efficient gas gap, it will add conservatism to the results since the values were calculated using a colder environment compared to MarsFAST expected thermal environment. The values shown in Table 17-3: were adjusted based on the various operational modes of the MarsFAST rover which were used for the sizing of the power sub-system.

CASE	Total	Day	Night
Cold Lat -5 Ls 82 OD 0.08 Hibernate, No Wind	320	174	145
Cold Lat -5 Ls 82 OD 0.08 Standby, No Wind	300	153	146
Cold Lat -5 Ls 82 OD 0.08 Hibernate, 30m/sec Wind	350	185	165
Cold Lat -5 Ls 82 OD 0.08 Standby, 30m/sec Wind	298	151	145
Cold, Lat -5 Ls 82 OD 2 Hibernate, 30m/sec Wind	333	176	158
Cold, Lat -5 Ls 82 OD 2 Standby, 30m/sec Wind	298	152	146

Table 17-3: Heater Energy Consumption in Whr for Mars Surface Operation for the Various Thermal Scenarios scaled from Exomars Rover 2018 predictions

17.5 List of Equipment

The following is the list of thermal equipment with the relative estimated mass.

Element 1	Rover			MASS [kg]			
Unit	Unit Name Click on button above to insert new unit	Part of subsystem	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
1	Heat Switches (Loop Heat Pipes)	Thermal	3	0.5	To be modified	10	1.7
2	Radiators	Thermal	3	0.4	To be modified	10	1.4
3	Insulation	Thermal	1	0.3	To be developed	20	0.3
4	Filer	Thermal	1	0.1	To be modified	10	0.1
5	Temperature Sensors	Thermal	161	0.0	To be modified	10	0.4
6	Heaters	Thermal	1	0.1	To be modified	10	0.1
-	Click on button below to insert new unit			0.0	To be developed	20	0.0
SUBSYSTEM TOTAL			6	3.5		10.7	3.8

Table 17-4: List of Thermal Equipment

17.6 Options

17.7 Technology Requirements

The following technologies are required or would be beneficial to this domain:

Included in this table are:

- Aerogel Insulation,

The remaining technology, such as the LHP heat switch, is currently under development through Exomars.

18 GS&OPS

18.1 Requirements and Design Drivers

18.1.1 Carrier Provided By NASA

The MarsFAST rover will be transported to Mars by a NASA spacecraft, and involvement from the ESA operations teams will only begin after the landing has been completed. Apart from infrequent checkouts (see section 18.3.2.2), no operations are scheduled for the launch and cruise phase. This differentiates the mission from other ESA missions, which usually have their most intense operations period during the Launch and Early Orbit Phase (LEOP). It is assumed that spacecraft operations are conducted by NASA and the rover is handed over to ESA once it has been safely landed on the surface. Operations have to be planned carefully so that all activities requiring the rover hardware are completed before launch (e.g., System Validation Tests). The lengthy cruise phase will be used for training and preparation activities that are independent of the flight hardware. ESA has gained experience with long periods of inactivity in previous interplanetary missions, e.g. Rosetta. Challenges regarding team training and team composition are therefore well known. The experience of the Huygens mission should be factored in, where the concept of having an ESA spacecraft carried by a NASA spacecraft was exercised.

18.1.2 Rover Operations Planning

The mission requirement to show the capability of covering several hundred metres per sol to reach the target of traversing at least 20 km in total makes it impossible to rely solely on path planning performed on ground. The ground planners cannot have detailed knowledge of the terrain far away from the current location; the rover thus needs to have a high level of autonomy to travel safely. The focus of the operations teams will be on providing goals and targets for the rover rather than meticulous planning of all rover movements. Despite the fast mobility requirements ESA is also expected to benefit on the overall rover operations experience gained on the current project ExoMars 2018.

18.1.3 Dependence On Sunlight

When operating the MarsFAST rover, power will have to be managed very carefully. The limited power available severely constrains the opportunities for downlinking data directly to Earth (see sections 7.3.3 and 18.3.2.2). It will also limit extended operations at night. The risk of losing the mission due to lack of sunlight during a dust storm will, in combination with the considered launch dates, put pressure on the operations teams to accomplish the mission objectives.

18.1.4 Martian Environment

The environment a spacecraft faces during nominal operations is fairly easy to predict: While atmospheric drag or solar winds might vary over time, the thermal and lighting conditions will be known. A Mars rover, in contrast, will have to deal with the Martian weather including dust storms. This means that the planning of operations needs to include higher margins during resource allocation, to be prepared for the unexpected. It has to be accepted that the simulation of operations before execution cannot be accurate (RD[55]). The difficult rover environment makes team training very important in order to ensure effective and safe rover operations and secure the capability of reacting to unforeseen situations and contingencies (RD[64]).

18.1.5 Constraints On Downlink

The timing of communications opportunities is crucial for operating a rover on Mars. In an ideal case, commands would be uplinked to the rover in the Martian morning. The ground would be monitoring the rover's progress throughout the day, or at the latest receiving all relevant data at the end of the day. The operations for the next Martian day could then be planned on ground during the Martian night. Such an operations concept could be implemented via direct-to-Earth communications or with a dedicated orbiter in a sun-synchronous orbit which is configured to provide flyovers of the rover site during local morning and evening. Direct-to-Earth communications would be the best solution from a scheduling point of view but its use will be constrained by the available power. As a result, only a subset of data will be transferred at operationally convenient times. Implications on the operations concept will be discussed in section 18.3.1.3.

18.2 Assumptions and Trade-Offs

18.2.1 Main Assumptions

The ground segment and operations concept presented in this section is based on the following main assumptions:

1. The MarsFAST mission will have sufficient priority to request any of the ESA 35 m Deep Space Antennas to support the communication passes (see section 18.3.3.3)
2. It will be possible to have operations teams working on Mars time for at least part of the mission duration (see sections 19 and 18.3.3.4)
3. During the cruise phase, there will be opportunities to receive telemetry and send telecommands to the rover via the NASA infrastructure (see section 18.3.2.2)

18.2.2 Trade-off: Communications Opportunities

Direct-to-Earth (DTE) communications are theoretically possible for the MarsFAST rover if the following two conditions are fulfilled:

- Daylight (i.e., between sunrise and sunset)
- Earth in sight (i.e., between Earthrise and Earthset)

In practice, minimum elevation angles, ground station availability, power and thermal constraints need to be taken into account, but the two conditions mentioned above can be used for a first estimate of the DTE communications opportunities. Figure 18-1 shows the four relevant events (Earthrise, Earthset, sunrise and sunset) for three examples from the range of latitudes considered for the 2024 and 2026 launch opportunities. The earliest, nominal, and latest mission time windows are indicated by overlapping semi-transparent grey areas.

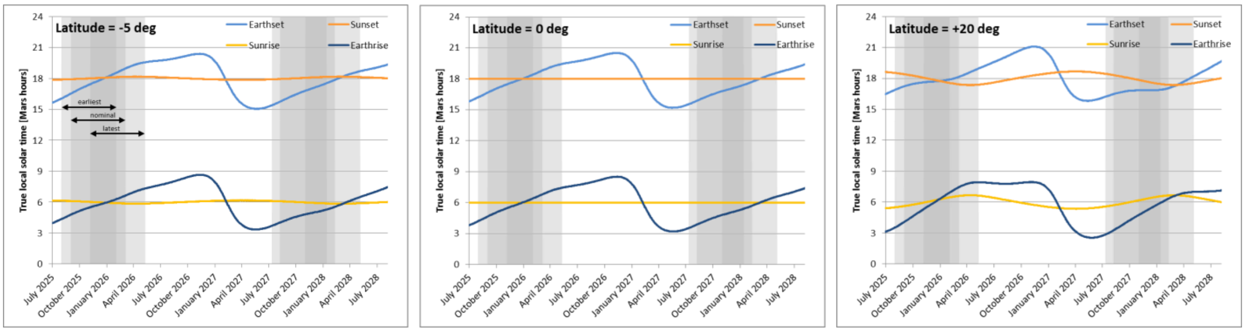

Figure 18-1: Local time of Earthrise, Earthset, sunrise and sunset for the minimum (left) and maximum (right) latitude considered, as well as for an equator location (centre)

The total time available with both conditions fulfilled is plotted in Figure 18-2 for the full latitude range -5° to +20° considered for MarsFAST. Depending on the latitude and season, the available time varies between approximately 9 and 12 hours, which would be suitable for the ideal case of uplinking a set of commands in the Martian morning to execute rover operations during the day and subsequently downlinking the results to Earth to facilitate planning of the next sol.

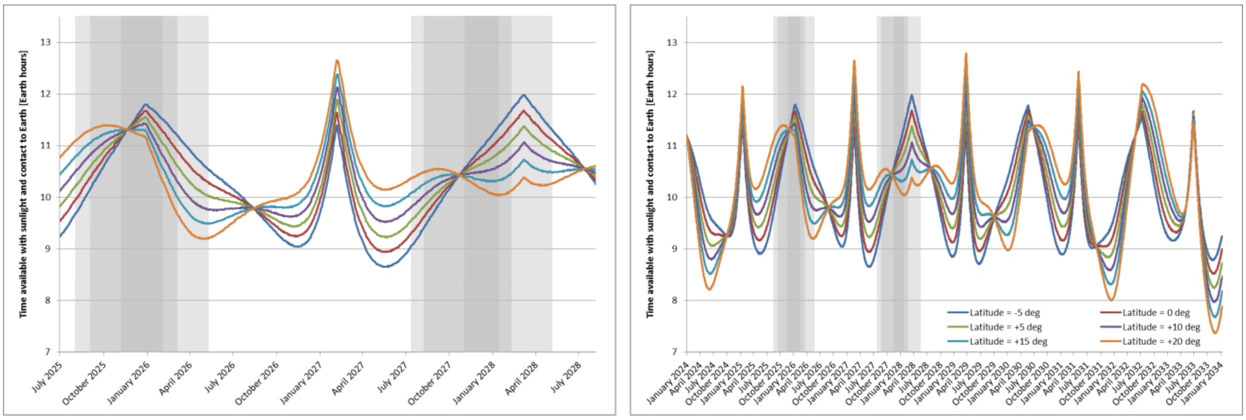

Figure 18-2: Time available with sunlight and Earth in sight. Left: focus on the 2024 and 2026 launch opportunities; right: Whole range of possible launch dates considered

However, while the uplink in the morning can be supported, downlinking all relevant data in the evening is not possible due to power and bandwidth constraints, so relaying data via Mars orbiters (a UHF link) needs to be considered since it allows higher bandwidths at significantly lower power consumption.

At this point in time it is impossible to predict which orbiters will be available during MarsFAST surface operations. It is rather unlikely that an orbiter in an ideal sun-synchronous orbit will be present that can provide a downlink opportunity every sol during the Martian evening, so the only realistic assumptions that can be made as of now are as follows:

- There will be at least two orbiter passes per sol
- A typical pass duration is in the order of minutes

- The time of the passes is likely to drift from sol to sol and might be impractical for operational purposes.

The NASA science platform that delivers the MarsFAST rover will also baseline UHF passes supported by the orbiters available, which could potentially lead to conflicts or to passes being shared between the missions.

18.2.3 Trade-Off: Working Hours Of The Ground Operations Teams

A day on Mars, or 'sol', is approximately 40 minutes longer than a day on Earth. Since the major rover operations require daylight, the rover operations schedule is linked to the Martian day and thus shifts by 40 minutes every Earth day. After a cycle of 36 sols, or approximately 37 Earth days, the cycle will start from the beginning.

For all Mars rover missions executed by NASA so far, the ground operations teams responsible for planning the rover operations adjusted their work schedules to follow Mars time for the first months of surface operations (RD[56]) since this approach allows the teams to respond quickly to the latest data received from Mars. After operations have finished in the Martian evening, data is transferred to Earth and, during the Martian night, used for planning the operations for the next sol.

This approach has the advantage that the maximum time available (between downlink and uplink opportunities) can be used for planning, thus increasing the operations efficiency and reducing the need for assumptions since planning can be based on the latest data. However, this way of working has proven to be demanding on personnel (RD[56], RD[65]). It has the potential to contribute to personnel fluctuations or human error, and can hardly be sustained over longer periods of time. The larger team sizes and personnel working on Mars time will be an important cost driver. NASA missions typically transition to standard Earth working hours after about 90 sols (RD[56]), which needs optimized planning tools and procedures and also requires certain compromises in situations where it is not reasonable to wait for the latest data.

For MarsFAST, in which the fast mobility demonstration takes place from sol 100 to sol 110, the following approach is proposed: Ground operations teams will follow Mars time until the end of the nominal mission (≥ 180 sols). After that a transition to Earth working hours could be attempted. Potential shift schedules will be discussed in section 18.3.3.4.

18.2.4 Trade-Off: Location of Operations Centres

Previous studies on Mars rover and surface operations missions (RD[9], RD[5], RD[62]) assume that the Mission Operations Centre (MOC) will be located at ESOC. In contrast, the ExoMars 2018 rover mission will be operated from the Rover Operations Control Centre (ROCC) provided by ALTEC, Italy.

The following points will have to be considered when deciding whether or not the ExoMars ROCC infrastructure can be reused for MarsFAST: As the launch dates of the two missions will be at least 6 years apart and the ExoMars rover is being designed for a nominal mission duration of 180 sols (RD[58]), it is unlikely that the teams and infrastructure of that centre would still be maintained at the time of MarsFAST surface operations. Furthermore, the use of non-ESA centres is only applicable if the project framework dictates the location of the centre, and no such requirements have been identified up to this point. Conducting rover operations from ESOC would have the advantage of reusing and sharing existing facilities (see section 18.3.3.1) with other missions. In addition, ESOC is currently building up rover operations competence within the framework of the Multi-Purpose End-to-End Rover Operations Network (METERON RD[59]). The following thus presents the operations concept option assuming a MOC located at ESOC.

The traditional ESA approach of separating the Science Operations Centre (SOC) from the MOC is usually considered unsuitable for rover missions, which favour an integrated approach with operations teams working closely with the scientists. This is especially important for missions where a clear separation between payload (i.e., the systems that will generate scientific results) and platform (i.e., the systems keeping the payload alive and operating) cannot be made. MarsFAST is such an example since the capabilities of the rover itself are also under scientific investigation.

The operations concept thus assumes that the mission scientists will collaborate closely with the operations teams for both high-level and day-to-day planning activities. In the early surface operations phases, the mission would benefit from having all major involved parties present at the location of the operations centre (RD[66]). For later phases a concept for remote access and collaboration should be considered for the mission scientists. Distributed operations and collaboration concepts are currently under investigation within the METERON framework (RD[59]).

18.2.5 Schedule Constraints

Rover operations on Mars will be severely affected by two major events: dust storms and solar conjunctions. Dust storms cannot be predicted; only statistical data is available for predicting the probability and impact of global dust storms. The corresponding model for the optical depth of the Mars atmosphere (see section 7.1.1) as a function of solar longitude and thus of the date is presented in Figure 18-3. The global dust storm season is indicated by an expected optical depth of > 4. For both the 2024 and 2026 launch opportunities, the global dust storm season can be avoided for arrival at or prior to the nominal time (see section 4.1).

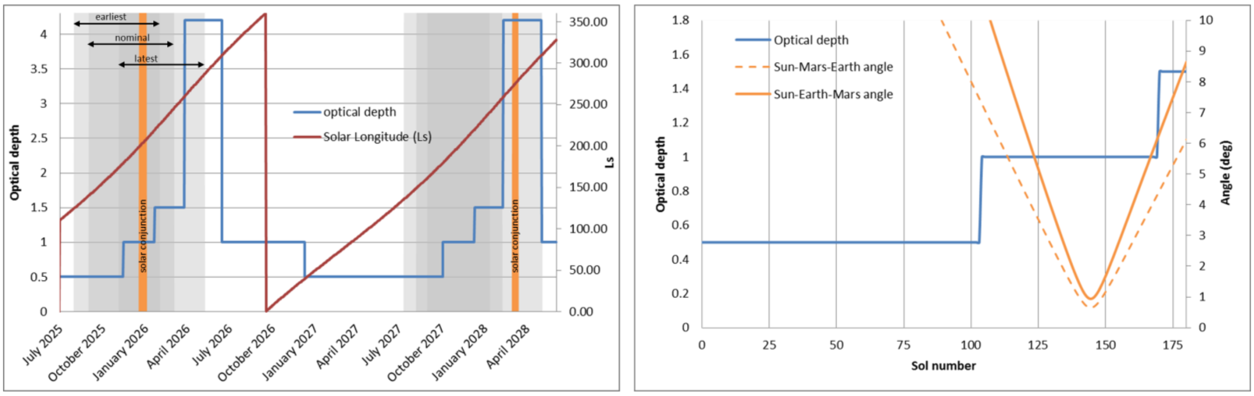

Figure 18-3: Left: Optical depth (blue), solar longitude (red) and solar conjunctions (vertical orange bars) for the 2024 and 2026 launch opportunities. Right: Optical depth and angles relevant for solar conjunction during the nominal mission duration of the 2024 launch opportunity

A solar conjunction will occur during the nominal mission window of the 2024 launch opportunity. This situation is characterised by a geometry in which the Sun is in between Earth and Mars, compromising communications between Earth and Mars rover.

The right-hand side of Figure 18-3 provides details on the relevant angles as a function of time (number of sols since the arrival date).The Sun-Earth-Mars angle (solid line; also see Figure 18-4) is relevant for receiving rover data (telemetry, images, and science data) on Earth. If the angle is too low the bitrate for the data stream needs to be reduced. Typically the first reductions are performed at about 3° (RD[57]) , which would correspond to a duration of 21 sols with limited or severely limited telemetry.

The Sun-Mars-Earth angle (dashed line) is relevant for transmitting commands to the rover. It will be below 3° for 32 sols for the conjunction occurring during the nominal mission time window.

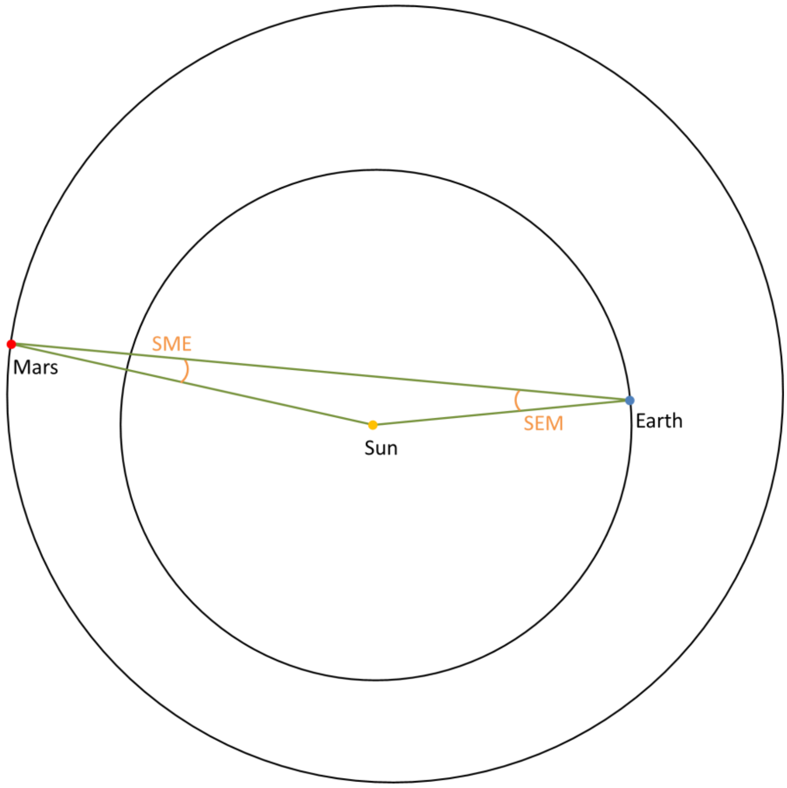

Figure 18-4: Earth - Sun - Mars geometry close to solar conjunction, indicating the Sun-Mars-Earth (SME) and Sun-Earth-Mars (SEM) angles

The exact impact of the conjunction geometry on which data transmissions are still possible depends on the margins in the link budget (see section 15.7.1). For all communications opportunities using Mars orbiters as a relay, MarsFAST will depend on the operational choices the orbiter operations team will be making. It is to be expected that relaying data for a rover mission has lower priority than ensuring the health of the orbiter in times of severely reduced bitrates.

The following approach, based on the assumption that an angle of SME = 3 deg is the limit for communications both via orbiters and the DTE link, has thus been considered: The rover shall be prepared for the conjunction event starting at an SME angle of 5 deg, and will be configured to hibernate for the time period during which SME < 3 deg (32 sols). Afterwards it will be readied for nominal operations, which will commence at SME = 5 deg.

18.3 Baseline Design

18.3.1 Operations Concept

18.3.1.1 Commanding

Due to the long one-way light times (OWLT) expected during surface operations (e.g., 19-20 minutes for the nominal mission duration associated with the 2024 launch opportunity) and the constraints on communications opportunities (see section 18.3.1.3), real-time operations are not feasible. All rover operations will be either pre-planned (i.e., time-tagged commands stored in an on-board schedule also known as Mission Timeline (MTL)) or autonomous (e.g., autonomous navigation, automated sequences triggered by predefined events, FDIR). This modus operandi is well known for interplanetary mission during their routine phase.

All communications passes will be prepared using time-tagged commands since these events are known well in advance. Various routine activities will be performed during the predefined passes, including:

- Pointing of the X band high gain antenna
- Switch-on/off of the transceivers (UHF or X band)
- Downlink of the latest as well as stored HKTM, log files, events and other health and status information
- Downlink of science data
- Management of on-board storage space
- Uplink of MTL updates and other software modifications.

18.3.1.2 Mission Planning

Off-line planning and coordination activities are normally done well in advance of execution and can be performed during normal working hours. These activities include the booking of ESTRACK resources to support the DTE passes as well as coordination with orbiter missions for supporting the UHF passes and exchanging relevant data.

The planning of rover operations is often categorized into either *strategic* (mid-term) or *tactical* (short-term) planning (RD[55],RD[60]). Strategic planning will include the following activities:

- High-level scheduling of science operations (i.e., allocations for science vs. traversing, interesting locations and targets)
- High-level goal planning for traversing (i.e. definition of the general direction and attempted average speed of the rover).

While strategic planning should be focused on a timespan of several weeks, tactical planning is concerned with the upcoming sols. The following activities will be performed regularly:

- Routine operations for pass management as described in section 18.3.1.1 (these operations can be prepared several sols in advance but depend on the outcome of strategic planning)
- Housekeeping, maintenance and calibration activities for both platform and payload
- Detailed operations planning for science activities
- Goal-based operations planning for traversing.

As mentioned earlier, every aspect of science operations will be controlled from the ground as no high level of autonomy is foreseen. Based on the latest science data available, the science team shall provide instrument command requests for integration by the operations team.

Due to the requirement of covering hundreds of metres a day, traversing cannot be planned in detail on ground since the operations team's knowledge about the terrain to be crossed is limited. The only way of traversing more than the immediate surroundings of the rover at time of planning is to rely on the rover's on-board system to evaluate the safety of a path and to choose an alternate plan if safety cannot be assured. The operations teams will operate the rover using goal-based commanding, providing the target locations rather than the exact path to follow. Navigation data received from the rover will have to be checked frequently to assure that the on-board autonomous navigation is working as expected, and to perform corrective action if required. No science can be accommodated during long traverses; thus dedicated traverse and science sols are planned (see section 7.3.3).

18.3.1.3 Communications strategy

Based on the constraints in available communications opportunities as discussed in section 18.2.2, the following communications strategy is proposed:

- In the Martian morning, the commands to be executed during the sol are uplinked via DTE
- During the day, every UHF opportunity is used to downlink all of the data that has been stored since the last pass (science data, images, HKTM, navigation data). Critical data will be prioritised
- If operations continue significantly after the last daytime UHF pass and if power constraints allow, a DTE pass for downlinking vital data can be scheduled (5-10 min duration depending on power resources). Together with the data received via UHF, the downlinked data can be used for preparing the TC uplink for the following sol
- If there is still stored data to be downlinked, a UHF pass at Martian night time can be scheduled.

18.3.2 Mission Phases

A timeline of the different mission phases has been presented in section 7.3.4. The operational activities that will take place during the different phases will be examined here in more detail.

18.3.2.1 Preparations phase

Operational preparations in the years leading up to the launch will follow a similar schedule as utilised for interplanetary missions involving spacecraft. The unique constellation of preparing an ESA rover to be transported by a NASA spacecraft will, however, require some modifications, including:

- Close cooperation, coordination and integration between the MOC and NASA. Note that the difference in time zones between the two centres should be considered
- Need for implementing an interconnecting data link between ESA and NASA for use during the cruise phase (see section 18.3.2.2)
- ESA validation activities (e.g., Mission sequence tests, System Validation Tests, RF Compatibility tests) will be complemented by activities in cooperation with NASA
- Field tests involving all science and operations teams will be beneficial to validating procedures and processes for rover operations planning in a realistic environment
- No need for an extensive simulations campaign before launch since the cruise phase can be utilised; simulations of the operations to be performed during the cruise phase may be scheduled pre-launch.

A duration of approximately 6 years is proposed for the preparation phase, similar to, e.g., MarsREX (RD[9]).

18.3.2.2 Launch and cruise phase

As the launch and cruise phase will be conducted by NASA, the involvement of the ESA operations team will be very limited, which will allow them to mainly focus on further preparations of the surface operations.

The lengthy cruise phase shall be used to conduct a simulations campaign verifying the readiness of all ground systems and teams and facilitate team training. Due to the integrated nature of the MOC/SOC, it would be beneficial for the science team to also participate in the simulations campaign so that the planning of rover operations under realistic conditions can be exercised.

Two opportunities to contact the MarsFAST rover during the cruise phase have been agreed with NASA. All data streams to and from the spacecraft will be handled by NASA, with data being relayed to and from the ESA ground segment. These checkouts will be used to verify rover health and safety, and it is assumed that they will also provide the opportunity to update the rover on-board software (OBSW) in case issues are identified during the simulations campaign (to be iterated with NASA). If no opportunity for OBSW patching will be possible during the cruise phase, these operations can still be performed after the rover has arrived on Mars, although this approach is not preferred since it would use up valuable surface operations time.

18.3.2.3 Deployment, checkout, egress

Since no real-time operations are possible and communications opportunities cannot be guaranteed, all of the critical deployments, especially of the solar arrays, will have to be performed autonomously by the rover. Deployment processes that are not time critical can be performed via ground commanding if required. A health and status check of the rover should be performed as soon as possible.

The egress phase needs to be controlled from the ground based on information received from NASA after landing as well as from images taken by the rover to assess which egress direction is safest. The data volume needed in order to make safe decisions will be high for this phase. It might be necessary to command the egress one step at a time, which will necessitate maximum coverage from orbiter missions to provide as many communications opportunities as possible. Even with several communications windows per day the egress process will be time-consuming since the time between sending a command and receiving information on the result of a command can easily be in the order of several hours.

All operations will be prepared and performed by the operations team located at the MOC, which will include rover engineering specialists. In addition, the rover Prime contractor shall provide rover engineering support.

18.3.2.4 Surface operations (commissioning, early operations, routine operations)

After egress is complete, all of the rover systems (platform and payload) will have to be thoroughly checked out. In determining the order of checkout and commissioning activities, care needs to be taken not to invalidate results by performing tests too close to the lander since that area might be contaminated. The rover's capability of traversing long distances autonomously should be tried and tested in an incremental approach, increasing the distance travelled per sol as more experience is being gained.

Operations tasks performed on ground will include

- Mission Planning as described in section 18.3.1.2
- Monitoring of rover health and safety
- Conduction of the DTE passes for uplink and downlink
- Offline performance analysis, data dissemination and archiving
- On-board software maintenance
- Maintenance of ESA ground facilities and network
- Coordination with orbiter missions for data relay opportunities.

All operations will be prepared and performed by the integrated operations/science team located at the MOC, with rover engineering support provided by the Prime contractor.

18.3.2.5 Disposal phase

The nominal mission duration for MarsFAST is 180 sols, which corresponds to 185 Earth days. Depending on the exact launch date, the global dust storm season might start shortly before or after the end of the nominal mission (see section 18.2.5), rendering the survival of the rover fairly unlikely but not impossible (i.e. depending on the maximum optical depth)

In case all mission objectives have been reached before the rover succumbs to either a failure or a lack of power, it is assumed that the mission will be terminated by shutting down the rover to avoid interference with current or future missions.

18.3.3 Ground Segment Design

This chapter will summarise and explain in detail how the requirements and drivers described earlier in the report will affect the design of the ground segment. The MarsFAST ground segment architecture will be similar to the architecture of existing interplanetary missions operated from ESOC. However, some fundamental differences exist. Their impact on the ground segment design is outlined below:

- No flying spacecraft under ESA control (see section 18.1.1)
  - No traditional launch and early orbit phase (LEOP) with 24/7 shifts required on the ESA side
  - As there is no need to prepare manoeuvres, the support required from Flight Dynamics will be limited to calculations of Earth/Mars visibility, timing of passes, and antenna pointing
  - Infrastructure for secure data transfer ESA <-> NASA will be required for operations during cruise phase
- No real-time rover operations (see section 18.3.1.1)
  - Main focus of the operations team will be Mission Planning
- Integrated science team (see section 18.2.4)
  - No need for a completely separated Science Operations Centre
  - Facilities for scientists connecting remotely during the later mission phases would be beneficial
- UHF passes conducted via relay orbiters (see section 18.3.1.3)
  - No dedicated MarsFAST ground station bookings required to support these passes
  - Infrastructures and processes for exchanging data with orbiter missions required.

An overview of the ground segment design based on these points is presented in Figure 18-5. For communicating with the rover, the MOC will have to interact either with the ESTRACK Control Centre (ECC) for the DTE passes, with orbiter operations centres for the UHF passes, or with NASA during the cruise phase. These interactions are indicated by red arrows.

In addition, there will be close collaboration between the integrated operations and science team located at the MOC and the MarsFAST project as well as the rover engineering support provided by the Prime Contractor.

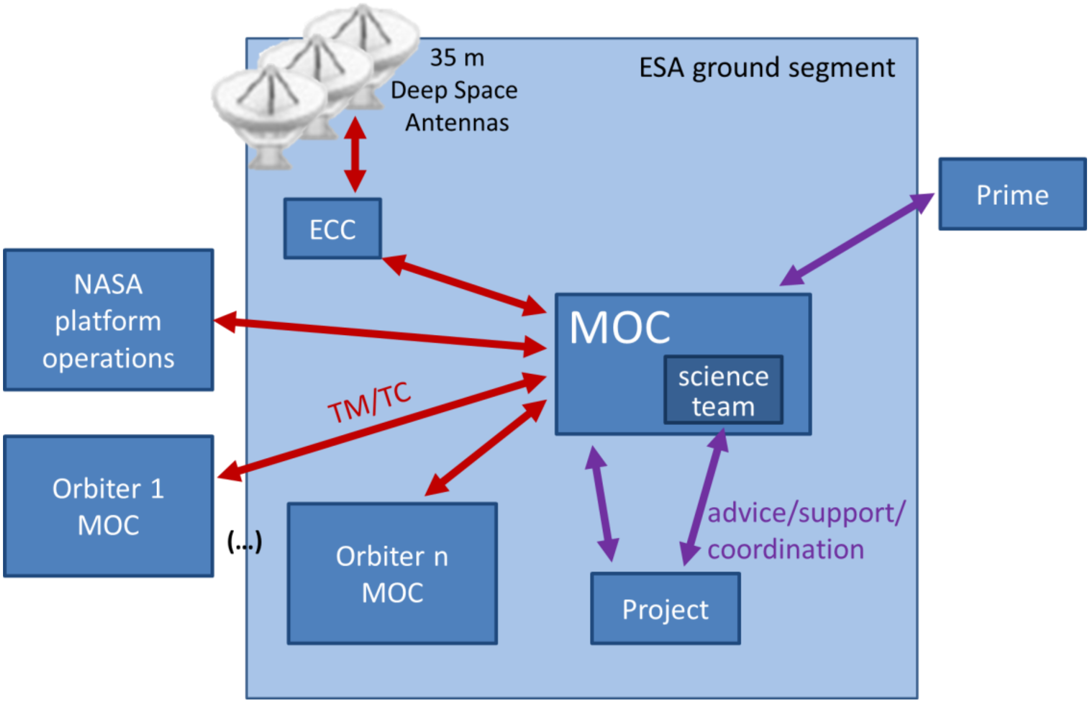

Figure 18-5: Ground segment design overview

18.3.3.1 Teams and facilities

The ESA ground segment will consist of the following teams and facilities:

- Operations
  - Flight Control Team (FCT)
  - Dedicated Control Room (use of Main Control Room during egress and checkout activities)
  - Project Support Rooms
  - Mission-specific software as outlined in section 18.3.3.2
  - Mission hardware for validation purposes (e.g., Engineering Model, rover test bed)
- Flight Dynamics
  - Mission Analysis (during preparation phase)
  - Flight Dynamics (during surface operations)
  - Respective computer hardware
- Ground Station Operations
  - Ground Stations (primarily the 35 m Deep Space Antennas - see section 18.3.3.3
  - Communications Network
  - ESTRACK Control Centre

- IT Infrastructure
  - Operations tools (e.g., MOIS)
  - Data analysis tools (e.g., MUST)
  - Archive and Data Distribution System, remote access infrastructure for scientists
  - MCS development infrastructure
  - OPSLAN (operational LAN) and interface hardware/software
  - Interface to NASA ground systems (for cruise phase operations)
  - Interface for data exchange with relay orbiter missions (ESA and/or NASA)
  - Maintenance teams.

18.3.3.2 Mission-specific ground systems software

On the ground segment side, three main software products will be required for MarsFAST operations: Mission Control System (MCS), Mission Planning System (MPS) and the operational simulator. The core functionality of all these systems is not specific to rover operations but can be reused from existing products developed for operating spacecraft. The specific functionality required for operating a rover will then have to be added in the customisation process.

Due to the time frame for which MarsFAST is scheduled, it is to be expected that the MCS core will be based on the European Ground Systems Common Core (EGS-CC, RD[61]) infrastructure. Details of the customisations required will depend on the communications protocols the rover will be using for communicating over the space link.

For the core functionality of the MPS, the existing MPS framework used by all missions can be reused, albeit with extensive adaptations to accommodate operating a rover instead of a spacecraft. A suite of ancillary tools for, e.g., visualisation, image processing or map generation will be needed as well. To support the short planning cycle described in section 18.3.1.2, a high level of automation is necessary for the data analysis process, which in turn requires a seamless integration of the various tools used to support operations.

The operational simulator is required for validating ground segment components and operations procedures, team training (especially during the simulations campaign) and safety checks of operations prior to execution. To make it suitable for rover operations, the simulator's capabilities have to go beyond what is usually implemented for spacecraft simulators. In addition to emulating the rover hardware and locomotion system, a realistic representation of potential terrains and their impact on both the products generated by the rover (e.g., panorama images) as well as the rover movement is required.

18.3.3.3 Ground station coverage

Since the cruise phase will be managed solely by NASA and all checkouts will be performed via the NASA ground systems, no ESA ground station coverage is required before surface operations commence.

During surface operations, contact to the rover will be established via X-band (DTE link) and UHF (for link to relay orbiters - see section 18.3.1.3). For the latter, the ground station coverage required to transfer the data between Earth and orbiter is not analysed here since it is assumed the coverage will be absorbed by the respective orbiter mission. The baseline is, however, to rely on UHF passes for downlinking data and use the X band DTE link for critical data as well as a backup.

In case of anomalies causing the rover to enter safe mode, recovery actions will have highest priority, and science data will be stored until the system is back to nominal. Help will be enlisted from all available orbiter missions in order to get maximum UHF coverage. Maximum support shall also be requested for the egress phase to allow quick decision making.

To facilitate DTE communications, the three ESA 35 m Deep Space Antennas (New Norcia, Malargüe, Cebreros) will be required. 30 minutes of TC uplink in the Martian morning and up to 10 min of TM downlink in the Martian evening will be requested per sol. It should be noted that these short pass durations do not constitute an efficient use of resources since the recharges to be paid for the use of Deeps Space Antennas are calculated based on whole hours. In case the rover power budget should allow longer communications windows, these could thus be accommodated easily without requiring additional resources on the ground segment side.

The proposed schedule makes it impossible to restrict the mission to using only one of the ground stations (see also section 18.2.1) since the required station is dictated by the time of day during which a pass needs to take place. Fortunately, due to the Earth-Mars geometry during the possible time windows considered here, which are located close to Mars solar conjunctions (see section 18.2.5), no conflicts exist with spacecraft missions located at the Earth-Sun Lagrange point L_2, the main users of the 35 m ground stations. Since L_2 is located on the Earth-Sun axis, on the side facing away from the sun, L_2 will be visible from a certain ground station at a very different time of day compared to Mars (see also Figure 18-4). As of now, scheduling conflicts might be expected with, e.g., the ExoMars Trace Gas Orbiter (in case it will still be operational at the time of MarsFAST operations) or possibly BepiColombo.

18.3.3.4 MOC Shift planning

As discussed in section 18.2.3, there is a benefit to having the operations team following the Mars schedule during the early phases of a Mars rover mission. This section will provide more details on what kind of shift schedules could be utilised.

Strategic planning (see section 18.3.1.2) should always be conducted during normal Earth working hours since it is concerned with the mid-term strategies and high-level goals.

Depending on external constraints, the tactical planning of a sol of rover operations can be conducted in different ways. The two possible cases are as follows:

(a) All relevant information from previous operations is available at the beginning of the planning process.
(b) Insufficient information about the previous sol's operations is available, but data from the sols before is complete.

Case (a) can only be achieved if the communications opportunities (see section 18.3.1.3) allow it **and** the operations team's shift can be aligned with the Martian night. If either of the two conditions is not met, case (b) applies (RD[63]).

During a sol, three different sets of tasks are required to be performed by the ground operations team:

- Execution of the DTE passes (FCT; for spacecraft missions this task is performed by a SPACON, often working for several missions). Data from the UHF passes will be available from the orbiter mission, and only validation of this data will be needed.
- Analysis of the received TM, science and navigation data (integrated team comprised of operations engineers, scientists, potentially also rover support from Prime contractor) to generate planning input for the upcoming sol → *Downlink team*
- Preparation of the TCs to be uplinked by integrating the latest inputs based on recent data with previously prepared operations (FCT) → *Uplink team*

Figure 18-6 and Figure 18-7 show two possible shift schedules for an example location of -5° N, 0° W during the first 36 Earth days of the nominal mission time window for the 2024 launch opportunity. In Figure 18-6 the ideal case (a) is plotted, assuming 8 hour shifts for both the *Uplink* and *Downlink* teams. This plot assumes that data analysis can start approximately at the end of the Martian day (for this particular example sunset is the limiting factor, but see section 18.3.1.3 for situations where Earthset is the cut-off point), that there will be some overlap between *Uplink* and *Downlink* teams to coordinate and that the *Uplink* team will then finalise the plan and either conduct the uplink themselves or hand it over to a SPACON-like position.

Due to the difference in the length of Earth and Mars day, the shift schedule will change by approximately 40 minutes every day, which has severe impacts on all affected personnel (RD[55], RD[56]).

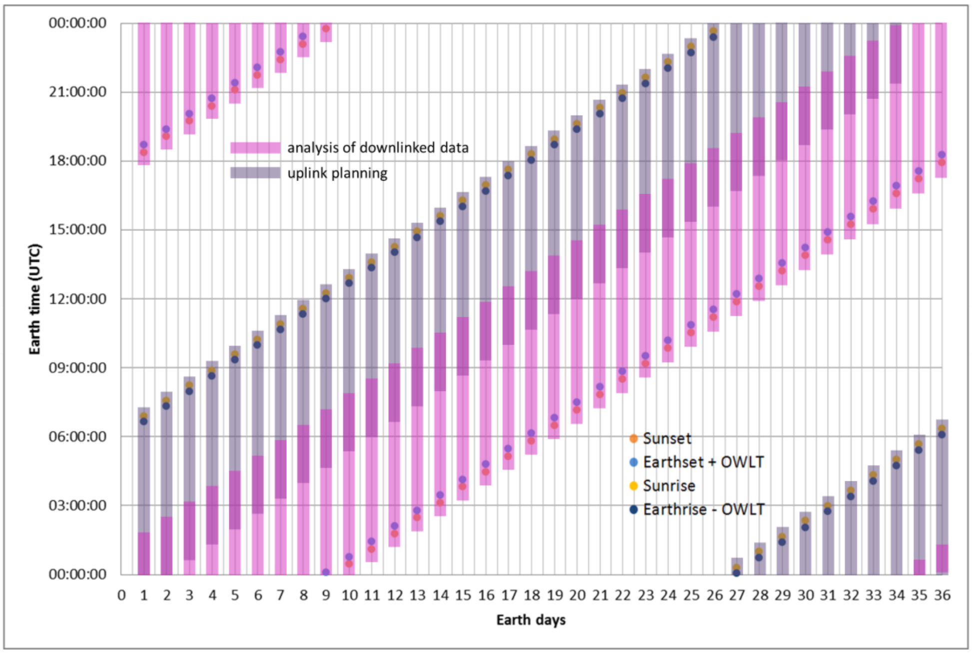

Figure 18-6: Potential MOC shift schedule: Operations teams working on Mars time

Figure 18-7 shows a shift schedule that tries to keep all operations within acceptable Earth working hours. In the middle part of the time window depicted here, the approach described above for scheduling the *Uplink* and *Downlink* shifts with minimal overlap can still be maintained. However, at the outer edges the overlap between the two shifts steadily increases which creates higher pressure and might lead to a smaller amount of operations being prepared and validated. During the remainder of the cycle it is not possible to work with recent data, and case (b) applies: Data from the sol before the current sol will have to be used as a baseline. In this situation the split between the *Uplink* and *Downlink* teams is not useful anymore, and the two teams should be combined into an integrated planning team that covers both functions. In this mode operations are effectively planned for two sols ahead.

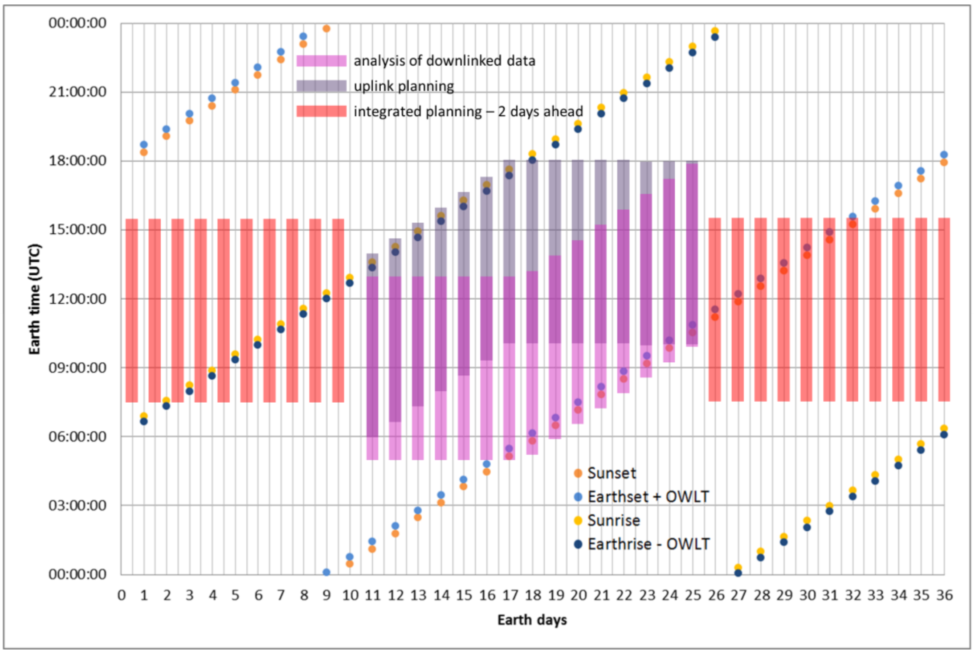

Figure 18-7: Potential MOC shift schedule: Operations teams working on Earth time

In case the times of communications opportunities are not as benign, a mixed approach might have to be used even in the early mission phases: Teams following the Mars schedule during phases where the data can be retrieved in time, and working Earth hours if it cannot.

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19 PROGRAMMATICS/AIV

This chapter describes the requirements and design drivers which are particularly important to achieve the programmatic goals for the MarsFAST study and the assumptions and trade offs made in this context. Accordingly, a programmatic approach is elaborated leading to a proposal for model philosophy, test matrix and a schedule estimate.

19.1 Requirements and Design Drivers

The main assumptions and design drivers from a programmatics point of view are:

- Launch not before 2024 by NASA
- Phase B2/C/D starting end 2017 TRL 6 (new ISO scale) achieved by end 2017, see RD[70]
- Phase A/B1 starting not later than Q1 2016
- International collaboration scenario: The ESA rover MarsFAST will be transported to Mars on a pallet provided by NASA/JPL, which is lowered onto the surface via the Sky-crane Entry Descent and Landing system.

19.2 Assumptions and Trade-Offs

Planetary Protection COSPAR category IVa would be enough for the MarsFAST rover mission concept, as its instruments are not dedicated to the investigation of extant Martian life. For the time being, the same assumption is taken for the NASA elements.

Note that in the context of MSR technologies demonstration, MarsFAST mission focused on the demonstration of the MSR "FAST" mobility capabilities and not in the compliance with the MSR Planetary protection categorisation, which will impose additional constraints to the MSR fetching rover design.

No RHUs will be used.

The ExoMars 2018 will be successfully implemented and operated. This assumption is important for the development schedule because the MarsFAST design is supposed to be based on strong heritage from the ExoMars 2018 rover mission.

The approach for exchange and sharing of documents, software and hardware and of the testing approach will be agreed with NASA early in the programme with bilateral agreements. In addition the responsibility for the control and operation of rover and egress system in the various system modes must be agreed.

19.2.1 Planetary Protection

Category IV missions comprise certain types of missions to a target body of chemical evolution and/or origin of life interest or for which scientific opinion provides a significant chance of contamination which could jeopardise future biological experiments.

Requirements imposed include rather detailed documentation (more involved than Category III), including a bioassay to enumerate the bioburden, a probability of contamination analysis, an inventory of the bulk constituent organics and an increased number of implementing procedures. The implementing procedures required may include trajectory biasing, cleanrooms, bioload reduction, possible partial sterilization of the direct contact hardware and a bioshield for that hardware.

(Extracted from RD[69]).

The planetary protection specific requirements will lead to an impact on AIV activities and therefore, an extension of the schedule, complexity and cost. The preliminary estimated increase of the schedule duration considering a category IVa mission as per chapter 19.2 is:

- 20% PFM units manufacturing time
- 20% PFM system integration time
- 10% PFM system testing time
- Final bioburden reduction:+3 weeks.

Advantage will be taken from the experience gained on other planetary exploration missions facing similar constraints. Bioburden control know-how and facilities heritage from ExoMars is assumed.

19.3 Technology Development

The Technology Readiness Levels (TRL) present a systematic measure, supporting the assessments of the maturity of a technology of interest and enabling a consistent comparison in terms of development status between different technologies.

The different TRL as defined in RD[70] are shown in Table 19-1:

TRL	ISO Definition	Associated Model
1	Basic principles observed and reported	Not applicable
2	Technology concept and/or application formulated	Not applicable
3	Analytical and experimental critical function and/or characteristic proof-of concept	Mathematical models, supported e.g. by sample tests
4	Component and/or breadboard validation in laboratory environment	Breadboard
5	Component and/or breadboard critical function verification in a relevant environment	Scaled EM for the critical functions
6	Model demonstrating the critical functions of the element in a relevant environment	Full scale EM, representative for critical functions
7	Model demonstrating the element performance for the operational environment	QM
8	Actual system completed and "flight qualified" through test and demonstration	FM acceptance tested, integrated in the final system
9	Actual system completed and accepted for flight ("flight qualified")	FM, flight proven

Table 19-1: TRL scale

Table 19-2 shows an indication of the development time depending on the current TRL. According to the European Space Technology Master Plan, to prepare the contractual basis for multi-annual programs it takes about 18 months to reach political agreement on financial ceiling. This has also been included in the table.

TRL	Duration
5-6	4 years + 1.5 year
4-5	6 years + 1.5 year
3-4	8 years + 1.5 year
2-3	10 years + 1.5 year
1-2	12 years + 1.5 year

Table 19-2: TRL: development duration

Few technologies and equipment, potentially to be used in the MarsFAST mission have not yet reached TRL 5, e.g. a Dual UHF/X-Band transponder, a low power FGPA/ASICI, metasurface HGA, rapid image processing (SPARTAN), MEMS IMU on a chip. Model Philosophy

The assumed model philosophy for the rover at System level includes:

- Structural Thermal Model (STM)
- Locomotion Breadboard
- Avionics Test Bench (ATB)
- Engineering and Qualification Model (EQM)
- Proto Flight Model (PFM)
- Spare equipment / kits.

The EQM is assumed not to be used as a source for spares, but to be kept as a reference model for the operational phase.

The Structural Thermal Model shall ensure the mechanical and thermal qualification of the rover main structural design, including mechanisms, and the overall thermal control design. It shall be used to correlate structural and thermal mathematical models.

The Locomotion Breadboard is proposed to allow the early development testing of the rover locomotion design, as it is one of the most critical elements of the rover.

The Avionics Test Bench will be used to validate the avionics design, to perform functional validation (software and protocol date exchanges and algorithms) and mostly to support the on board software versions verification and validation. This validation should be performed in closed loop which simulates computer environment and where sensors or units are simulated.

The Engineering Qualification Model will allow the development and verification of the rover navigation procedures and mission operations. During the mission, it will also be used in support of the Rover Operations Control Centre activities, to take decisions on how to progress with the mission (try off-nominal manoeuvres before their actual execution on Mars surface, etc). Egress testing will be repeatedly carried out on this model, to ensure the rover egress from the pallet. The EQM can undergo environmental qualification, so the related tests can be done earlier in the schedule flow.

The Protoflight Model will be used for acceptance testing and may be subjected to delta qualification. All its equipment will be either FM units, having passed acceptance testing as required, or PFM units having passed their qualification testing.. The environmental testing of the PFM might be reduced in favour of EQM testing to reduce the bio burden and the risk of compromising the cleanliness and contamination control status.

The above presented model philosophy allows a decoupling of activities on the different models and thus, introduces programme flexibility and reduces schedule risks. In addition, the assembly and test activities on the individual models can be performed, at least in parts, in parallel to each other to further reduce time expenditure. In order to save costs, a number of suitable GSE may be reused from other projects.

19.4 Options

No options are identified which could impact the principal programmatics and AIV approach.

19.5 Test Matrix

Table 19-3 shows the different tests to be performed on the different models proposed for MarsFAST.

Test description	ATB	STM	EQM	PFM
Handling/Integration		X	X	
Mechanical Interface		X	X	
Mass Property		X	X	X
Electrical Performance	X		X	X
Functional Test	X		X	X
Deployment Test		X	X	X
Telecommunication Link	X		X	X
Alignment		X	X	X
Static Load		X	X	
Shock/Separation		X		X
Sine Vibration		X		X
Modal Survey		X		
Acoustic		X		X
Outgassing		X	X	X
Thermal balance		X	X	

Test description	ATB	STM	EQM	PFM
Thermal vacuum			X	X
Grounding/Bonding		X	X	X
EMC conducted emission and susceptibility			X	
EMC radiated emission and susceptibility			X	
RF testing			X	
Egress testing			X	X

Table 19-3: Test Matrix

It is essential to agree early in the programme with NASA on the models to be delivered and testing approach, in particular on the extent of the testing of rover and egress system in Europe and on the (re-)testing, including test levels, applied at system level in the US.

19.5.1 Environmental Tests

The environmental tests, as requested above, shall demonstrate that the rover operates nominally under environmental conditions corresponding to the worst cases of the mission.

Static load test: This test is required to demonstrate that the structure is able to support the static load constraints corresponding to the design load and is considered as part of the qualification sequence.

Modal survey test: This test is considered as part of the qualification sequence and performed on the STMs only. It shall be combined with the sine vibration tests, as it consists in particular measurements performed during the low level tests using specific test instrumentation.

Sine and acoustic vibration tests: These tests are considered as part of the qualification sequence and performed at qualification level and duration on the STM. They are also considered as part of the acceptance sequence of the PFM and will be performed nominally at acceptance level and duration except if a delta qualification is required after the STM test results analysis.

Separation and shock test: This test has been considered from the mechanical point of view only and should be performed on the STM as part of the mechanical qualification. This test could be repeated at PFM level with the rover in electrical operational configuration (potential impact of the shock on electronic units, relays and electrical contacts – potentiality to provoke spurious signals or transient spikes).

Electromagnetic compatibility tests: The measurements to be performed depend on the EMC specification; during this test phase an adapted System Functional Test (SFT) should be performed.

Thermal balance test: The thermal balance test will verify the thermal model and the thermal control efficiency and performance. This test should be performed with the

STM in a vacuum chamber with solar simulation. This complete thermal balance test shall simulate several significant mission cases.

Thermal vacuum (cycling) test: The thermal cycling test is proposed as part of the acceptance sequence in addition to the limited thermal balance test. It would enable the verification of the spacecraft operation in cold and hot cases corresponding to the expected limit temperatures. For these two cases the adapted SFT should be repeated.

Dust environment: Tests simulating Mars environment including dust should be considered for development tests or functional tests with suitable models, e.g. with the EQM - however these tests have not been specifically mentioned in the Test Matrix Table 19-3. They are expected to be performed in parallel with the mentioned tests, thus not driving the schedule.

19.5.2 Ground Segment Compatibility

The objective of the ground segment interface verification is to validate the operations requirements of the spacecraft in conjunction with the different elements of the ground segment, hardware and software compatibility.

The MarsFAST mission operations would be conducted from a specific Rover Operations Control Centre (ROCC). For this study, it has been assumed this ROCC will be based on the one developed for ExoMars.

The verification program should cover all rover operations modes necessary to fulfil the mission objectives. This means, the rover will be operated in an interactive mode allowing acquisition of housekeeping and scientific data and the instrument control via the RF link.

The ground segment interface verification support activities should be conducted based on the ROCC test procedures and test reports, which will have to be derived from the MarsFAST documents such as the Rover Telemetry and Telecommand Data Base.

The emphasis of the ground segment interface validation shall be given to the compatibility tests between the rover and the mission control system, and the rover and the ground station RF link.

System Validation Test (SVT)

System validation tests have to be performed in order to allow compatibility testing between the rover and the mission control system, using the protoflight model connected to the control centre for direct telecommand and telemetry. The validation test shall concentrate on one side on the detailed housekeeping and science data streams from the command links to the rover, and on the other side on the operational aspects.

These tests could also cover the validation of the control centre operations software and the rover flight software using the rover telemetry data base. The data shall contain telemetry in the specified formats and bit rates. The data contents shall be close to in-flight data contents (as far as possible) and shall be generated in the course of preceding rover integration tests.

RF Compatibility Test

For RF compatibility tests a RF suitcase model is needed, representing the rover RF and Data Management System (DMS). This allows the validation of the RF up-link and down-link compatibility with the ground station.

This could also include the verification of all telemetry and telecommand, as well as telemetry formats, bit rates, packet types and link budget measurements and also all MarsFAST command types at DMS level.

19.6 Schedule

According to the different requirements and assumptions, a schedule for the MarsFAST mission has been developed. The different project phases, their sequence and duration together with the main reviews are depicted in Figure 19-1.

The schedule is based on a five days working week; public holidays are not counted.

The critical path is indicated by red bars in the Gantt chart.

The schedule shows also a typical estimation of development times needed for technology and equipment with low TRL to reach the required TRL 6 (ISO) before the implementation phase B2/C/D. Accordingly any technology/equipment which has not reached TRL 4 by today requires accelerated development to reach the required maturity in time.

ID	Task Mode	Task Name	Duration	Start	Finish
1		**MarsFast Project Milestones**	**2384 days**	**Mon 04/01/16**	**Thu 20/02/25**
2		Project kick-off	0 days	Mon 04/01/16	Mon 04/01/16
3		Preliminary Requirements Review (PRR)	0 days	Fri 30/12/16	Fri 30/12/16
4		System Requirements Review (SRR)	0 days	Thu 31/08/17	Thu 31/08/17
5		Preliminary Design Review (PDR)	0 days	Thu 28/02/19	Thu 28/02/19
6		Critical Design Review (CDR)	0 days	Thu 04/06/20	Thu 04/06/20
7		Qualification Review (QR)	0 days	Thu 13/01/22	Thu 13/01/22
8		Payload need date	0 days	Thu 23/02/23	Thu 23/02/23
9		Rover Acceptance Review (AR	0 days	Thu 23/11/23	Thu 23/11/23
10		Latest Delivery Date of the Lander to NASA	0 days	Thu 30/05/24	Thu 30/05/24
11		NASA System Flight Acceptance Review (FAR)	0 days	Thu 14/11/24	Thu 14/11/24
12		Launch	0 days	Thu 20/02/25	Thu 20/02/25
13		**Phase A/B1 (20 month)**	**434 days**	**Mon 04/01/16**	**Thu 31/08/17**
14		Phase A (12 month)	260 days	Mon 04/01/16	Fri 30/12/16
15		Phase B1 (8 month)	174 days	Mon 02/01/17	Thu 31/08/17
16		Contract preparation (6 month)	130 days	Fri 01/09/17	Thu 01/03/18
17		**Phase B2/C/D(69 month)**	**1500 days**	**Fri 02/03/18**	**Thu 30/11/23**
18		Design	320 days	Fri 02/03/18	Thu 23/05/19
19		STM manufacturing	230 days	Fri 24/05/19	Thu 09/04/20
20		STM integration	40 days	Fri 10/04/20	Thu 04/06/20
21		STM testing	70 days	Fri 05/06/20	Thu 10/09/20
22		ATB manufacturing and testing	300 days	Fri 24/05/19	Thu 16/07/20
23		Locomotion Breadboard manufacturing and testing	320 days	Fri 24/05/19	Thu 13/08/20
24		EQM units manufacturing	200 days	Fri 19/06/20	Thu 25/03/21
25		EQM units testing	120 days	Fri 26/03/21	Thu 09/09/21
26		EQM integration	90 days	Fri 10/09/21	Thu 13/01/22
27		EQM testing	200 days	Fri 14/01/22	Thu 20/10/22
28		PFM units manufacturing	240 days	Fri 10/09/21	Thu 11/08/22
29		PFM units testing	140 days	Fri 12/08/22	Thu 23/02/23
30		PFM integration	90 days	Fri 24/02/23	Thu 29/06/23
31		PFM testing	90 days	Fri 30/06/23	Thu 02/11/23
32		Final bio burden reduction	15 days	Fri 03/11/23	Thu 23/11/23
33		Shipment to NASA facilities	5 days	Fri 24/11/23	Thu 30/11/23
34		Contingency (6 month)	130 days	Fri 01/12/23	Thu 30/05/24
35		**NASA system activities with rove**	**190 days**	**Fri 31/05/24**	**Thu 20/02/25**
36		Integration onto NASA lander	30 days	Fri 31/05/24	Thu 11/07/24
37		NASA system level verification	90 days	Fri 12/07/24	Thu 14/11/24
38		Shipment to launchsite	5 days	Fri 15/11/24	Thu 21/11/24
39		Launch campaign (3 month)	65 days	Fri 22/11/24	Thu 20/02/25
40		NASA contingency	130 days	Fri 21/02/25	Thu 21/08/25
41		**Critical technology development**	**1560 days**	**Mon 05/01/15**	**Fri 25/12/20**
42		From TRL 4/5 to TRL 6	520 days	Mon 05/01/15	Fri 30/12/16
43		From TRL 3/4 to TRL 6	1040 days	Mon 05/01/15	Fri 28/12/18
44		From TRL 2/3 to TRL 6	1560 days	Mon 05/01/15	Fri 25/12/20

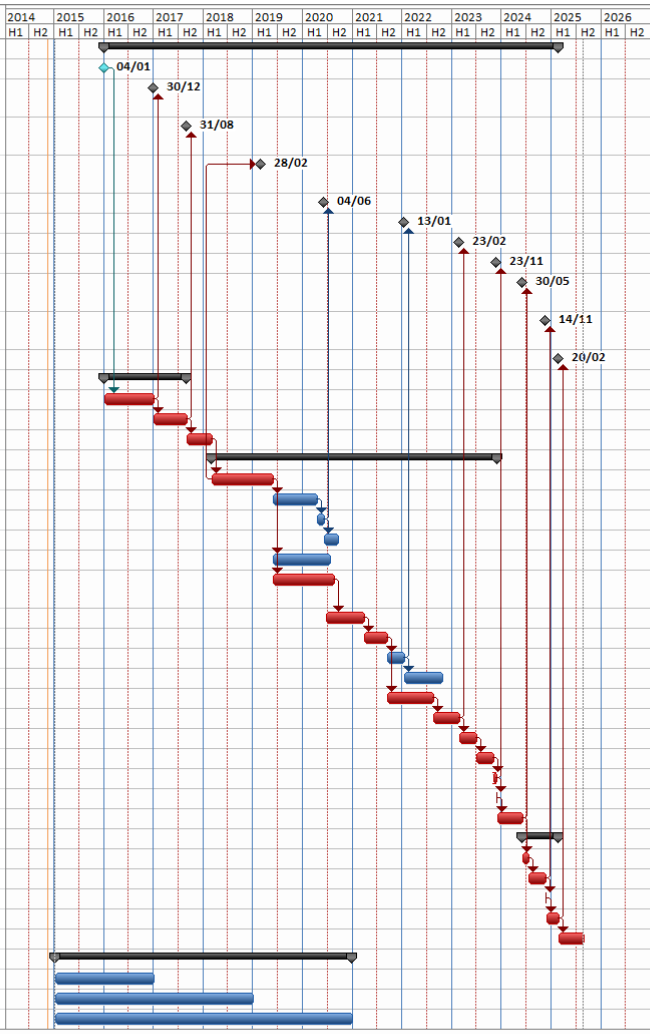

Figure 19-1: MarsFAST schedule

19.7 Summary and Conclusions

The presented schedule is an engineering estimation based on experience. It is driven by the technology level (e.g. reduction of development effort), use of heritage (e.g. reduction of procurement level), timely readiness of the payloads and the planetary protection level. It is essentially using the same task durations as for the MarsREX CDF study.

A phase A/B1 starting in 2016, as required, and lasting 20 months has been included. During this time, industrial studies will be performed, with parallel contracts.

Phase B2/C/D is starting early 2018 and has a duration of almost 6 years.

In line with the requirements TRL 6 has to be achieved as a minimum early 2018 and before B2/C/D, i.e. TRL 4 should have been achieved by today.

Considering a category IVa mission as per chapter 19.2, planetary protection extents the schedule (included).The rover will be ready for delivery to NASA/JPL late in 2023 or early in the first half of 2024 if the Agency contingency of 6 month is needed. A launch as assumed in 2024 requires the reduction of the duration of some tasks. This should be possible drawing on experience with the ExoMars 2018 rover.

For the integration and verification activities of the MarsFAST rover inside the NASA lander, a duration of 120 days has been assumed. This is a first estimation that could be used as a baseline, due to the non availability of further and more detailed information from NASA was exchanged during the framework of this CDF.

Verification sharing with NASA requires special attention, i.e. qualification sharing at European level & at NASA level must be agreed, as well as acceptance testing in Europe (tbc) and final system level acceptance tests in US. Special attention is also required for document exchange agreements and for agreements on control and operation of the European systems (rover and egress system). Bi-lateral agreements with NASA must be negotiated accordingly during Phase A to be properly taken into account before SRR.

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20 COST

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21 CONCLUSIONS

21.1 Satisfaction of Requirements

The study concluded in a feasible mission design compatible with the mission objectives and the requirements presented in sections 3 and 7.1. This report presents the design outcome.

Note that the initial mass allocations were 150 kg for the rover and 50 kg for the egress system. Despite the rover mass slightly exceeds its allocation, the total mass of 178 kg is below the total 200kg JPL mass allocation.

The requirements were satisfied with the following exceptions and limitations:

- The presented design allows for a verification of the fast roving capability of the rover without completing the overall distance required for the MSR mission. In favour of increasing the science output, the time for mere fast roving was limited to a verification period, which has been selected so as to allow for the validation of the performances and robustness of the fast roving approach – under real environmental and operational constraints with a high level of confidence: The timing was selected to be as late as possible for aging and dust deposition representativeness, yet to still ensure sufficient time for the validation before the solar conjunction. The rover target distance per day during the validation, thus the rover speed, is equivalent to cover the full MSR distance in case the whole operations lifetime of the rover was used for traversing.
- The current design ensures survival in hibernation mode in worst case conditions for only 12 days, instead of 14. Since these conditions occur at the end of the designed rover lifetime (i.e. solar panels with lowest efficiency due to accumulated dust) and worst case latitude, a loss of the rover due to a local dust storm at this time was considered acceptable.
- Only limited DTE communication will be possible due to the power limitations. Transmitting the science data to Earth in a DTE only architecture requires favourable conditions (long illumination, low power consumption of other subsystems) to allocate enough energy to the transmission. In the worst case scenarios a DTE time of ore than 5 min. could not be realised.

21.2 Further Study Areas

Some aspects were identified during the study that will require further dedicated consideration in the future:

- Definition of science case supported by a Study Science Team: It became evident during the study that a strong science case is vital for the mission to not only be a technology demonstrator of MSR fast mobility capabilities. The science payload selected in this study identify one possible area of science investigations, but can also be understood as payload model on the rover. With their accommodation it was tried to cover a wider range of different possibilities for a future selection of rover payload, either on a mast, on a robotic arm or in the rover body.

- Science operations: With a selection of the science case, the detailed science operations will have to be defined. An operational science approach for the selected instruments is presented in the study within the given boundary conditions regarding power and communications. A more detailed definition will have to take into account these constraints, as well as the MSR fast roving verification objectives.
- Detailed thermal modelling and assessment: Due to the lack of RHUs, all thermal management has to rely on electrical energy or passive means. The necessary thermal heating power contribution was scaled from current ExoMars rover thermal models and assumptions as it was assumed to be a good design guideline. Detailed thermal models specific of the MarsFAST configuration and environment might yield to potential power savings in later design iterations.
- NASA interface: Thermal dissipation during the check-outs in cruise will have to be revisited, as well as communication possibilities in flight via the platform and before egress. General feedback suggested the possibility of communication via the NASA interface, yet no details have been defined. Next design phases should consider to provide more consolidated interface assumptions between ESA/NASA as early as possible.
- Landing time and first night survivability: The current design does not allow for a survival of the first night (following 24 hours on rover batteries prior to EDL plus one hour after touchdown for platform stabilisation), if the solar arrays cannot be deployed before to provide (some) battery recharge. Initial NASA feedback suggests a landing time that will be sufficiently early for critical deployments before the first night and some battery re-charge, but this will have to be consolidated. A potential risk mitigation to this constraint would be to carry an additional primary battery for first night survival.

21.3 Final Considerations

The 2024 launch possibility is considered as a baseline for this study. Any later launch date would lead to a (considerably) shortened surface operations time between landing and global dust storm occurrence at OD>4. This would negatively impact on the mission timeline and the mission objectives.

The rover power budget, the mission timeline, and the operations plan are based on worst case scenarios to ensure the achievement of mission objectives. In case of additional power available due to more favourable environmental conditions (e.g. more favourable latitudes), less power consumption of other subsystems (e.g. thermal), less dust deposition (e.g. low OD periods, frequent cleaning of solar arrays by the wind as was the case for the MER rovers) , or simply earlier in the mission, an updated operations plan yields potential benefits in longer roving times, longer usable time during the day, additional instrument operations, or longer DTE communication time.

No dust removal system has been baselined, due to the initial performance degradation of such a system (in the case of an electrodynamic device) and the limited mission lifetime, due to the global dust storm season. The use of a dust removal system has been identified as beneficial for long lifetime surface missions providing they ensure survivability at high optical periods during dust storm season. This could be used for

- Aggregation of additional data on navigation and roving performance, and mechanical wear of the locomotion subsystem
- Further verification of the fast roving capabilities
- Additional science output.

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22 REFERENCES

RD[1] Planetary Surface Dating Instrument, Summary Report, M. Jain, 2011, ESA contract 21506/08/NL/IA

RD[2] Jain, M. et al., 2012. Development of a luminescence planetary surface dating instrument. Geophys. Res. EGU General Assembly. Abstracts 14.

RD[3] Wolters, S.D. et al., 2013 WatSen: design and testing of a prototype mid-IR spectrometer and microscope package for Mars exploration. Experimental AstronomyAstrophysical Instrumentation and Methods © Springer Science+Business Media Dordrecht 201310.1007/s10686-012-9328-8

RD[4] WatSen: A combined IR spectrometer, Microscope and Humidity sensor, 2010 Summary Reportv 1.01 WS-OU-PS-SR, ESA contract no. 19751

RD[5] MNSM Mars Network Science Mission, CDF-124(A) December 2011.

RD[6] May R.D. et al., 2001 The MVACS tunable laser spectrometers, JGR, Vol. 106, NO.E8, pp. 17673-17,682.

RD[7] Le Barbu T., Parvitte B., Zéninari V., Vinogradov I., Korablev O., Durry G., Diode laser spectroscopy of H2O and CO2 in the 1.877 µm region for the in situ monitoring of the Martian atmosphere, Applied Physics, B, 82, 133-140, 2006

RD[8] MREP SFR Payload Definition Document Issue 1-0

RD[9] MarsREX – Mars Sampling and Rover Exploration Mission, CDF Study Report, CDF-89(A), dated July 2009

RD[10] MREP Sample Fetching Rover_ASTRIUM Design_SFR-ASU-TN003 Iss 1 Rev 1

RD[11] MREP Sample Fetching Rover_TAS Design _SD-DD-AI-0011 Iss2

RD[12] MREP and MREP-2 Technology Development Plans

RD[13] INSPIRE Technology Development Status Report and related RDs

RD[14] MREP Mars Environmental Specification

RD[15] ESA Planetary Protection Requirements_ESSB-ST-U-001

RD[16] Selection of the Mars Science Laboratory Landing Site, Golombek, Space Sci Rev (2012) 170:641–737

RD[17] Sample Fetch Rover, Preliminary Design Report, Issue 1, December 2011

RD[18] http://futureplanets.blogspot.nl/2013/06/the-next-four-mars-landers.html

RD[19] http://www.hexcel.com/products/aerospace/aengineered-core

RD[20] http://www.neaelectronics.com/products/hold-down-and-release-mechanisms/

RD[21] Concurrent actuator development for the Mars Exploration rover instrument deployment device, Fleischmen, R. available online at : http://www.mdacorp-us.com/Robotics%20Papers/IDD%20Actuators.pdf

RD[22] Preliminary Design Document and Scalability Analysis, Study report, B-U. Halter, 2.1, 28/06/2013

RD[23] Traverse Performance Characterization for Mars Science Laboratory Rover – JPL 2013

RD[24] P. Oettershagen, S. Michaud. Development and Validation of a Modular Parametric Analytical Tool for Planetary Exploration Rovers. iSairas 2012 Conference.

RD[25] Kucherenko, V., Bogatchev, A., van Winnendael, M. "Chassis Concepts for the ExoMars Rover", 8th ESA Workshop on Advanced Space Technologies for Robotics and Automation, Noordwijk, 2004

RD[26] R. McCoubrey, J. Smith, A. Cernusco, S. Durrant, P. Poulakis, R. Phillips, S. Jessen, H. Jones, P. Fulford. Canada's Suspension and Locomotion Subsystem for ExoMars 2018. 65th International Astronautical Congress, Toronto, Canada, 2014.

RD[27] Requirements Development, Verification, and Validation Exhibited in Famous Failures; Terry Bahill and Steven J. Henderson; Systems Engineering, Vol. 8, No. 1, 2005

RD[28] Autonomy in ESA Planetary Robotics Missions, ESA, G. Visentin, March 2007

RD[29] "SPAring Robotics Technologies for Autonomous Navigation (SPARTAN)", Final report, GMV, v1, 31/07/2013

RD[30] "Miniaturised MEMS based IMU on a chip". Internal ESA project. SoW by Stephen Airey.

RD[31] "NG FPGA (MUSE)". Internal ESA project. Contact David Merodio.

RD[32] Experimental Evaluation and Analysis of Electrodynamic Screen as Dust Mitigation Technology for Future Mars Missions, Rajesh Sharma, Member, IEEE, Christopher A. Wyatt, Jing Zhang, Member, IEEE, Carlos I. Calle,Nick Mardesich, and Malay K. Mazumder, Member, IEEE, IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 45, NO. 2, MARCH/APRIL 2009.

RD[33] Low Temperature Li-ion Battery ESR: Executive Summary Report, LTB-RP-ABSL-BA-0085;

RD[34] StrIn - Norway: Regenerative Energy Storage System for Space Exploration Missions, Final Presentation.

RD[35] ECSS-E-50-05C. Radio Frequency and Modulation Standard, 6 March 2009.

RD[36] CCSDS Proximity-1 Space Link Protocol--Physical Layer. Blue Book. Issue 4. December 2013.

RD[37] Lander Compact dual UHF/X-Band Frequency Communications Package Study (DUX) Final Report. A. W. Ballard, M. Cosby, S. Kynaston, M. Cassidy. QINETIQ/TS/AS/TN1200551. September 2012.

RD[38] Mars Science Laboratory Telecommunications System Design. Andre Makovsky, Peter Ilott, Jim Taylor. Jet Propulsion Laboratory, November 2009. http://descanso.jpl.nasa.gov/DPSummary/Descanso14_MSL_Telecom.pdf

RD[39] Sample Fetching Rover Study, Preliminary design, Astrium, December 2011

RD[40] Sample Fetching Rover Study, Detailed design report, Thales-Alenia-Space, June 2012

RD[41] ExoMars Trace Gas Orbiter (TGO) , Giacinto Gianfiglio, March 2014, http://exploration.esa.int/jump.cfm?oid=46475

RD[42] The Electra Proximity Link Payload for Mars Relay, Telecommunications and Navigation, Charles D. Edwards, Jr., Thomas C. Jedrey, Eric Schwartzbaum, and Ann S. Devereaux, Jet Propulsion Laboratory, Ramon DePaula, NASA Headquarters, Ramon DePaula, NASA Headquarters, May 2004. http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/7832/1/03-2150.pdf

RD[43] GMV-SEXTANT-FR

RD[44] Airbus SCOC3 http://www.space-airbusds.com/en/equipment/scoc3.html

RD[45] Aeroflex GR712RC http://gaisler.com/index.php/products/components/gr712rc

RD[46] Development and Analysis of the Surface Thermal Environment for the Exomars Lander Mission, Stephane Lapensee, Coralie Alary, ESA, AIAA-2010-6190

RD[47] Apparent thermal inertia and the surface heterogeneity of Mars, Nathaniel E. Putzig a,b,∗,1, Michael T. Mellon, Received 15 August 2006; revised 14 April 2007,Available online 27 June 2007

RD[48] Development of the Surface Thermal Environment for the Mars Scout Phoenix Mission, Glenn T. Tsujyki, ICES Paper 2007-01-3239

RD[49] Thermal Design of the ExoMars Rover Module, C. Alary and S. Lapensée ICES 2010

RD[50] Surface Downward thermal radiation and ground temperatures on Mars 1D software detailed design document, Fancois Forget, Ehouarn Millour, April 15 2009

RD[51] Viking Lander Surface Pressure Measurement, http://www-k12.atmos.washington.edu/k12/resources/mars_data-information/pressure_overview.html

RD[52] Mars Climate Database, http://www-mars.lmd.jussieu.fr/mars/access.html

RD[53] JMARS (Java Mission-planning and Analysis for Remote Sensing) is a Java-based geospatial information system developed by the Mars Space Flight Facility at Arizona State University. http://jmars.asu.edu/

RD[54] Thermal Design and Analysis of the Phoenix Mars Lander Meteorological Instrument, Stephane Lapensee and Darius Nikanpour, ICES 2007-01-3240

RD[55] Working the Martian Night Shift, A.H. Mishkin, D. Limonadi, S.L. Laubach, D.S. Bass, Robotics Automation Magazine 13, pp 46-53, June 2006, http://dx.doi.org/10.1109/MRA.2006.1638015

RD[56] Choosing Mars time: analysis of the Mars Exploration Rover experience, IEEE Aerospace Conference 2005, D.S. Bass, R.C. Wales, V.L. Shalin, pp. 4174–4185, March 2005, http://dx.doi.org/10.1109/AERO.2005.1559722

RD[57] MEX_ESC_TN-5733, Mars Express 2011 Solar Conjunction Operations: Lessons Learned and Guidelines for Future Operations

RD[58] http://exploration.esa.int/mars/45787-rover-surface-operations/

RD[59] METERON CDF report, CDF-96(A), dated December 2009

RD[60] The Mars Science Laboratory Supratactical Process, SpaceOps 2014 Conference, D. Chattopadhyay, A. H. Mishkin, A.R. Allbaugh, Z. N. Cox, S. W. Lee, G. H. Tan-Wang, 02/05/2014, http://dx.doi.org/10.2514/6.2014-1940

RD[61] http://www.egscc.esa.int/

RD[62] MREP ASR CDF report, CDF-109(A), dated October 2010

RD[63] Calculation of Operations Efficiency Factors for Mars Surface Missions, SpaceOps 2014 Conference, S. Laubach, 02/05/2014, http://dx.doi.org/10.2514/6.2014-1778

RD[64] Squyres, Steve. Roving Mars: Spirit, Opportunity, and the Exploration of the Red Planet. New York: Hyperion, 2005.

RD[65] Wiens, Roger. Red Rover. New York: Basic Books, 2013.

RD[66] Clancey, William J. Working on Mars: voyages of scientific discovery with the Mars Exploration Rovers. Cambridge: MIT Press, 2012.

RD[67] ECSS-E-ST-10-02C, “European Cooperation for Space Standardization, Space Engineering, Verification”, 6 March 2009. http://www.ecss.nl

RD[68] ECSS- E-ST-10-03C, “European Cooperation for Space Standardization, Space Engineering, Testing”, 1 June 2012. http://www.ecss.nl

RD[69] “COSPAR Planetary Protection Policy”, 20 October 2002, amended 24 March 2005, 20 July 2008; approved by the Bureau and Council, World Space Council, Houston, Texas, USA; prepared by the COSPAR/IAU Workshop on Planetary Protection, 4/02, with updates 10/02; 1/08. http://cosparhq.cnes.fr/Scistr/PPPolicy(20-July-08).pdf

RD[70] “Guidelines for the use of TRLs in ESA programmes”, ESSB-HB-E-002, Issue 1, Revision 0, 21 August 2013.

RD[71] Cost Risk Assessment Procedure, TEC-SYC/GRE/SA/2005/021_03, TEC-SYC, November 2006

RD[72] Mars Pathfinder, NASA's National Space Science Data Center, http://www.solarviews.com/eng/path.htm

RD[73] Mars Pathfinder Mission Information, NASA Planetary Data System, http://starbrite.jpl.nasa.gov/pds/viewMissionProfile.jsp?MISSION_NAME=MARS%20PATHFINDER

RD[74] How the Mars Exploration Rovers Work, Marshall Brain, 09 January 2004, http://science.howstuffworks.com/mars-rover3.htm

RD[75] NASA to Send Two Rovers to Mars in 2003, SPACE.com, Craig Linder, 10 August 2000, http://www.space.com/scienceastronomy/solarsystem/mars_rovers_000810.html

RD[76] TEC-SYC Cost Risk Procedure, TEC-SYC/5/2010/PRO/HJ, February 2010

RD[77] ESA Cost Engineering Charter of Services, Issue 4, TEC-SYC/12/2009/GRE/HJ

RD[78] Technology Readiness Levels Handbook for Space Applications, TEC-SHS/5551/MG/ap, Issue 1 Revision 6, Dated September 2008

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23 ACRONYMS

Acronym	Definition
ADE	Actuator Drive Electronics
AIT/V	Assembly, Integration and Test/Verification
AIV	Assembly, Integration and Verification
ARL	Automation and Robotics Lab (of ESA D/TEC Automation and Robotics Section)
ASIC	Application Specific Integrated Circuit
ATB	Avionics Test Bench
ATR	Attenuated Total Reflection spectrometer
AVM	Avionics Validation Model
BB	Bread Board
BEMA	Bogie Electro-Mechanical Assembly
C&DH	Command and Data Handling
CAN	Controller Area Network
CCSDS	Consultative Committee on Space Data Systems
CMA	Cost Model Accuracy
COSPAR	Committee on Space Research
DELIAN	Dextrous Lightweight Arm for Explorations (ESA TRP activity)
DEM	Digital Elevation Map
DFE	Direct From Earth
DMM	Design Maturity Margin
DMS	Data Management System
DOA	Degree of Adequacy of the Cost model
DoF	Degrees of Freedom
DTE	Direct to Earth
DUX	Dual UHF/X-Band Transponder
ECC	ESTRACK Control Centre
EDL	Entry Descent and Landing
EGP	Effective Ground Pressure
EGS-CC	European Ground Systems Common Core
EIRP	Effective Isotropic Radiated Power

Acronym	Definition
EMC	Electromagnetic Compatibility
EPC	Electric Power Conditioner
EPE	External Project Events
EQM	Engineering Qualification Model
ERC	Earth Re-entry Capsule
ESA	European Space Agency
ESOC	European Space Operations Centre
ESTRACK	European Space TRACKing network, ESA's G/S network
FCT	Flight Control Team
FDIR	Failure Detection, Isolation and Recovery
FM	Flight Model
FPGA	Field Programmable Gate Array
G/S	Ground Station
G/T	Antenna Gain to noise Temperature, the figure of merit of a receiver
GNC	Guidance, Navigations and Control
GSE	Ground Support Equipment
HDRM	Hold Down and Release Mechanism
HFoV	Horizontal Field of View
HGA	High Gain Antenna
HKTM	Housekeeping telemetry
HPA	High Power Amplifier
HW	HardWare
I/O	Input/Output
IMU	Inertial Measurement Unit
IQM	Inherent Quality of the cost Model
ITAR	International Traffic in Arms Regulations
LAN	Local Area Network
LEOP	Launch and Early Orbit Phase
LGA	Low Gain Antenna
LMD	Meaning of the acronym
Ls	Solar Longitude

Acronym	Definition
MCD	Mars Climate Database
MCS	Mission Control System
MEMS	Micro Electro-Mechanical Systems
MER	Mars Exploration Rover (NASA/JPL mission)
METERON	Multi-Purpose End-to-End Rover Operations Network
MLI	Multi Layered Insulation
MOC	Mission Operations Centre
MOIS	Mission Operations Infrastructure System
MPS	Mission Planning System
MSL	Mars Science Laboratory (NASA/JPL mission)
MTL	Mission TimeLine
MUST	Mission Utility and Support Tool
NASA	National Aeronautics and space administration
OBC	On-Board Computer
OBSW	On-board software
OD	Optical Depth
OPSLAN	Operational LAN
OSL	Optically Stimulated Luminescence dating
OSL	Optical Science Laboratory
OWLT	One-way light time
PFM	Protoflight Model
PMT	Photo Multiplier Tube
POE	Project Owned Events
QIV	Quality of the Input Values
QM	Qualification Model
RA	Robotic Arm
RF	Radio Frequency
RHU	Radioisotope Heater Unit
ROCC	Rover Operations Control Centre
SADM	Solar Array Deployment Mechanism
SEM	Sun-Earth-Mars angle

Acronym	Definition
SEU	Single Event Upset
SFT	System Functional Test
SLAM	Simultaneous Localization And Mapping
SME	Sun-Mars-Earth angle
SOC	Science Operations Centre
SPACON	Spacecraft Controller
SPARTAN	"Mars Sample Fetching Rover: SPAring Robotics Technologies for Autonomous Navigation", name of a past ESA R&D activity which produced hardware logic (on FPGA) of computer vision algorithms needed by Martian rovers for visual navigation and localisation tasks.
STM	Structural Thermal Model
SVT	System Validation Test
SW	SoftWare
TAS	Thales Alenia Space
TC	Telecommand
TCS	Thermal Control Subsystem
TGO	Trace Gas Orbiter
TM	Telemetry
TRL	Technology Readiness Level
TT&C	Telemetry Tracking and Command
UHF	Ultra High Frequency (300MHz-3GHz)
V&V	Validation and Verification
vSLAM	Visual Simultaneous Localisation and Mapping