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MISSION DESIGN OVERVIEW FOR THE MARS EXPLORATION ROVER MISSION

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Abstract

In the summer of 2003, NASA will launch the next wave of robotic explorers towards the planet Mars. Specifically designed to "follow the water", two identical rovers will be delivered to the surface of Mars to remotely conduct geologic and atmospheric investigations. The two self sufficient mobile science laboratories will be able to traverse large distances (over half a kilometer) during their three month surface missions while performing in-situ analysis of a number of rock and soil targets which may hold clues to past water activity. The project, appropriately named the Mars Exploration Rover (MER) project, will conduct fundamentally new observations of Mars geology, including the first micro-scale study of rock samples, as well as a detailed study of surface environments for the purpose of calibrating and validating orbital remote sensing data. Developing a baseline strategy to successfully achieve the objectives of such an ambitious mission involves integrating a variety of activities into a coherent plan, including: interplanetary trajectory and navigation design, atmospheric entry, descent, and landing (EDL) design, and surface mission planning. These activities, collectively referred to as mission design, are described in chronological order as the mission progresses through six mission phases: Launch, Cruise, Approach, EDL, Post-Landing Through Egress, and Surface Operations.

Mission Overview

The Mars Exploration Rover (MER) project has a primary objective of placing two mobile science laboratories on the surface of Mars to remotely conduct geologic investigations, including characterization of a diversity of rocks and soils that may hold clues to past water activity. The MER project will use the 2003 launch opportunity to deliver two identical rovers to different sites in the equatorial region of Mars. For at least 90 sols (or 90 Martian days) after the landing day, the two rovers will explore the landing sites and gather imaging, spectroscopy, composition data, and other measurements about selected Martian soils, rocks, and the atmosphere.

Science Objectives

The primary science goal of the MER mission is to determine the aqueous, climatic, and geologic history of a pair of sites on Mars where conditions may have been favorable to the preservation of evidence of pre-biotic or biotic processes - or stated simply, the MER mission has been designed to "follow the water" on Mars. The MER rover is essentially a robotic field geologist equipped to read the geologic record of a site with strong evidence of past liquid water. The high-level science objectives of the MER mission are indicated in Table 1.

Table 1: Science Objectives

• Search for and characterize a diversity of rocks and soils that hold clues to past water activity
• Investigate landing sites which have a high probability of containing physical and/or chemical evidence of the action of liquid water
• Determine the spatial distribution and composition of minerals, rocks, and soils surrounding the landing sites
• Determine the nature of local surface geologic processes from surface morphology and chemistry
• Calibrate and validate orbital remote sensing data and assess the amount and scale of heterogeneity at each site
• Identify and quantify iron-bearing minerals indicating aqueous processes
• Characterize the mineral assemblages and textures of different types of rocks and soils and put them in geologic context
• Extract clues related to past environmental conditions and assess whether those environments were conducive for life

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Mission Summary

The first Mars Exploration Rover (referred to as MER-A) will be launched by a Boeing Delta II 7925 launch vehicle from Space Launch Complex 17A (SLC-17A) at the Cape Canaveral Air Force Station (CCAFS) in Florida. The second MER mission, MER-B, will be launched using a more powerful version of the Delta II launch vehicle, the Delta II 7925H, from SLC-17B at the Cape. Both missions utilize 18-day launch periods and constant arrival dates at Mars in order to simplify operations. The launch and arrival dates are indicated in Table 2.

Table 2: Launch and Arrival Dates

Mission	Launch Period Open	Launch Period Close	Mars Arrival
MER-A	May 30, 2003	June 16, 2003	January 4, 2004
MER-B	June 25, 2003	July 12, 2003	January 25, 2004

The MER mission is divided up into six distinct mission phases. The phases are indicated in Table 3.

Since accurate navigation and delivery at Mars is critical to the success of the MER mission, a series of six trajectory correction maneuvers (TCMs) are planned during the Cruise and Approach phases to accurately delivery the spacecraft to their intended entry conditions. Approximately 7 months after launch the MER spacecraft will enter the Martian atmosphere directly from the interplanetary trajectory.

Similar to the Mars Pathfinder mission, the MER entry trajectory will follow an unguided, ballistic descent. It will rely on a heatshield and parachute to slow its descent through the Martian atmosphere, fire retro-rockets to reduce its landing speed, and finally deploy airbags to cushion its impact with the surface. After the airbag assembly rolls to a stop, the lander will retract the airbags, right itself, and deploy the lander petals. The rover will then deploy its solar panels completing the Entry, Descent, and Landing (EDL) phase of the mission.

In contrast to the Mars Pathfinder mission which used a retrograde entry and landed early in the Martian morning, both MERs will approach Mars on a posigrade trajectory and will land early in the Martian afternoon. The Earth will be in view during EDL allowing the transmission of signal tones, coded to indicate the accomplishment of critical steps during the EDL timeline. In addition to the X-band direct-to-Earth (DTE) signals, the Mars Global Surveyor (MGS) spacecraft will be called into duty to relay descent information via a UHF link.

The MER missions arrive at Mars in late southern summer. As a result, the Sun is just south of the Martian equator and moving north. Since the rover is solar powered, potential landing sites had to be constrained to a narrow latitude band near the equator in order to allow the rover to receive enough energy to survive for at least 90 sols on the surface. As a result the MER-A rover will be targeted to a landing site within a 20° latitude band extending from -15° (or 15° South) to +5° (or 5° North). Since the MER-B mission arrives 3 weeks later, the 20° latitude band was shifted slightly northward extending from -10° to +10°.

Final landing sites have not yet been selected, but the list of candidate sites has been narrowed from nearly 200 to just 4. Landing site selection is a complex process in which flight system engineering constraints are balanced against science goals in an attempt to identify safe landing sites while still allowing the project's science objectives to be met. Some of the engineering constraints currently being considered in landing site selection process include: landing site altitude, surface slopes, rock abundance, roughness, radar reflective properties, temperature, latitude (as it contributes to mission lifetime), and winds.

Table 3: Mission Phases

Mission Phase	Definition	MER-A Open Phase Start	MER-B Open Phase Start
Launch	Launch to thermally stable, positive energy balance state and the launch telemetry has been played back	May 30, 2003	June 25, 2003
Cruise	End of Launch phase to Entry-45 days	May 31, 2003	June 26, 2003
Approach	Entry-45 days to Entry	November 20, 2003	December 11, 2003
EDL	Entry to end of critical deployments on Sol 1	January 4, 2004	January 25, 2004
Post-Landing Through Egress (PLTE)	End of EDL to receipt of direct-to-Earth (DTE) transmission following successful placement of the rover wheels on the Martian surface	January 4, 2004	January 25, 2004
Surface Operations	End of PLTE to End-of-Mission	January 7, 2004	January 28, 2004
End-of-Mission (EOM)	Successful receipt of last scheduled UHF data return the night of Sol 91	April 6, 2004	April 27, 2004

High winds have turned out to be one of the more serious landing safety concerns, since high winds exacerbate the landing hazards due to rocks and slopes. Two interesting sites in the Valles Marineris canyon, were recently eliminated due to concerns regarding high horizontal winds. As a result, identifying "wind safe" or "low wind" landing sites has become a priority for the MER project, even to the extent of relaxing some of the other engineering constraints (such as the landing site latitude constraint). A final decision on landing site selection will be made shortly before launch. The current list of candidate landing sites is indicated in Table 4 and illustrated in Figure 1. The two Elysium sites were recently identified as "low wind" sites. A single Elysium site will be selected shortly resulting in a total of 4 remaining candidate sites.

Table 4: Candidate Landing Sites

Landing Sites	MER Landing Site		Location (IAU/IAG 2000)	
	MER-A	MER-B	Areocentric Latitude (deg)	East Longitude (deg)
Gusev Crater	√		-14.64	175.298
Hematite in Terra Meridiani	√	√	-2.06	354.008
Isidis Planitia	√	√	4.22	88.148
Elysium 1 * Elysium 2 *		√	11.73 14.32	123.958 115.438

* A single Elysium site will be selected after further analysis.

Following landing on Sol 1, it will take at least through Sol 4 to complete the Post-Landing Through Egress phase. Egress of the rover consists of a carefully choreographed series of steps by the rover, each initiated by the ground only after verification that the previous step has been successfully executed. The main egress activities for Sols 2-4 are deployment of the rover mobility system, severing the final cable connections with the lander, and surveying the Martian landscape with a stereo panoramic camera (Pancam) and infrared imager (Miniature Thermal Emission Spectrometer) for a safe egress path. The lander has no further function or capability after the egress is complete so there will be no pictures of the rovers themselves in operation on the surface.

The Surface Operations phase is planned to run through Sol 91. Daily communication with Earth occurs through the rover's X-band system. Communications will be augmented whenever Mars Odyssey or MGS overflights make UHF relays possible.

Each rover will use a stereo pair of Navigation cameras (Navcams) in addition to the Pancam on the mast, to image prospective travel paths and science targets. Front and rear mounted stereo hazard cameras (Hazcams) will assist the rover in autonomously traversing to a desired site. The rovers are capable of traveling as far as 40 meters in a single sol.

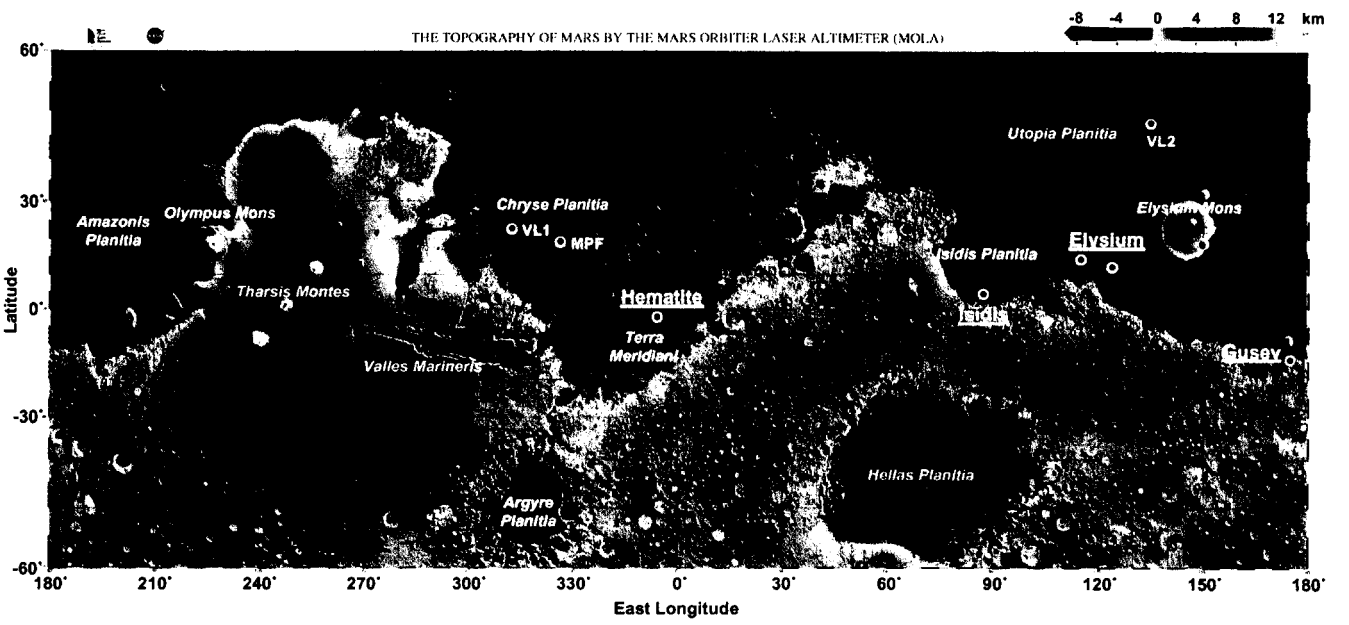


Figure 1: Map of Candidate Landing Sites

In addition to the long-range, remote sensing instruments mounted on the rover solar array deck, the rover is equipped with a 5 degree-of-freedom (DOF) arm, known as the Instrument Deployment Device (IDD). The IDD supports another set of instruments designed to closely observe rock and soil targets. The four devices on the science turret at the end of the IDD are a Mössbauer spectrometer (MB), an Alpha Particle X-ray Spectrometer (APXS), a Microscopic Imager (MI), and a Rock Abrasion Tool (RAT). The rock abrasion tool will remove the outer surfaces of rocks, to allow analysis of the freshly exposed, less weathered material. The IDD instruments will provide composition data about selected surface soil and rocks, including their elemental chemistry, iron content, and fine-scale morphology. Surface operations will be directed by the flight team, in order to the select the most promising rock and soil targets.

The life of the rover is driven by Mars' diurnal cycle, and thus, linked directly to sunrise and sunset. During the middle of a typical Martian day the rover might drive towards a target and/or take remote sensing data of the surface or of the atmosphere. It typically takes at least two, and often three sols to place an instrument on a specific target after the target has been selected by the flight team using remote sensing images. Mission scenarios show that each rover will be able to take detailed in-situ measurements of up to half a dozen individual targets during the 90 sol mission.

Towards the end of the Surface Operations phase, both power and telecommunications capabilities will be decreasing, as the Earth and the Sun become more distant from Mars, dust falls on the solar panels, the batteries lose capacity, and the Sun moves further north past the landing site latitude. The rover's ability to drive significant distances and the amount of time that the rover can stay awake each day will diminish with time. Eventually, somewhere near Sol 91 it is expected that the rover will be unable to store up enough thermal or battery energy to prevent its components' overnight temperatures from falling below their flight allowable levels. This will sooner or later result in failure of one or more of these components, silencing the rover forever.

A high-level overview timeline for the MER missions is given in Figure 2. The timing of the phases of the two missions are shown, relative to geometric data for Earth, Mars and the Sun.

Mission Success

In addition to the high-level science objectives stated earlier, NASA has levied a set of performance requirements on the Mars Exploration Rover mission which constitute the requirements for achieving Full Mission Success. The requirements for Full Mission Success are indicated in Table 5.

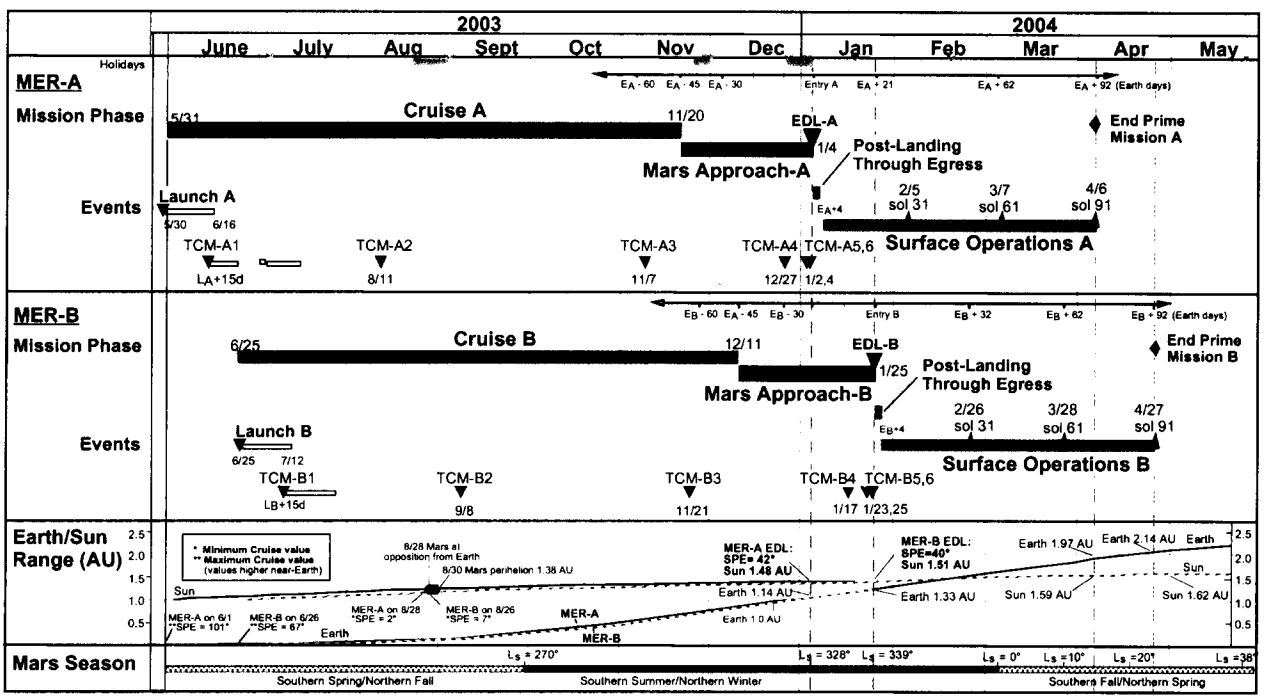


Figure 2: Mission Timeline

Table 5: Full Mission Success Criteria

• Launch two identical lander/rover missions to Mars during the 2003 launch opportunity, from the Eastern Test Range aboard separate Delta II-class expendable launch vehicles.
• The MER-2003 rovers shall each acquire science data and conduct in-situ analysis for 90 sols, and shall be designed for operations independent of the lander.
• At each landing site, operate the Athena instrument suite (i.e., Pancam, Mini-TES, Alpha Particle X-ray Spectrometer (APXS), Microscopic Imager, and Mössbauer spectrometer) during the 90-sol operational phase of the rover mission.
• At each landing site, acquire at least one full-color and at least one stereo 360° panoramic image of the landing site with the Pancam, with a resolution of less than 0.3 mrad per pixel. Acquire at least one image of a freshly exposed Mars rock that is also analyzed by another Athena instrument (i.e., Microscopic Imager, Mini-TES, APXS, or Mössbauer spectrometer).
• Drive the rovers to a total of at least eight separate locations and use the instrument suite to investigate the context and diversity of the Mars geologic environment. Every reasonable effort shall be made to maximize the separation between investigation locations to increase site diversity, without compromising overall mission safety or probability of success.
• To investigate complex science operations on remote planetary surfaces, the MER-A and MER-B missions shall operate simultaneously on the surface of Mars for a period of at least 30 sols.
• At least one of the rovers shall demonstrate a total traverse path length of at least 600 m, with a goal of 1000 m.

Flight System Description

The MER flight system consists of four major components: an Earth-Mars cruise spacecraft or cruise stage, an atmospheric entry, descent, and landing (EDL) system or aeroshell (consisting of a heatshield and a backshell), a lander, and a mobile science rover with an integrated instrument package. The cruise and EDL systems are similar to the systems used to deliver the Mars Pathfinder lander to the surface of Mars in 1997. The rover design is based on the Athena Rover (carrying the Athena science payload) which began development under the Mars 2001 project. Figure 3 illustrates the major components of the MER flight system. A breakdown of the masses of the flight system components is indicated in Table 6.

Table 6: Flight System Mass Breakdown

Flight System Component	Allocated Mass (kg)	Cumulative Mass (kg)	Staged Mass
Rover	185	185	Mobile mass
Lander (with airbags)	348	533	Landed mass
Backshell / Parachute	209	742	
Heat Shield	78	820	Entry mass
Cruise Stage	193	1013	
Propellant	50	1065	Launch mass

Cruise Stage

During the interplanetary transfer to Mars, the cruise stage provides most of the traditional spacecraft subsystem functionality (such as propulsion, power, communications, thermal, and attitude control). The cruise stage, however, is commanded by the flight computer which is tucked away inside the rover.

The propulsion system consists of a monopropellant hydrazine system equipped with two spherical Titanium propellant tanks and two diametrically opposed thruster clusters each containing four 4.4 N thrusters. The thruster clusters are mounted on the +X and -X axes of the spacecraft. Each thruster is mounted 40° off of the X axis with two thrusters in the X-Z plane and two in the X-Y plane. The propulsion system is used for spin-rate control, attitude control, and all trajectory correction maneuvers (TCMs).

During the Cruise and Approach phases, the spacecraft is powered by triple junction $GaInP_2/GaAs/Ge$ solar arrays mounted in an annulus on the outer ring of the cruise stage. The array is divided into 5 sections, 3 of which can be switched on- or off-line via ground command as needed. With all strings on-line the array has a peak power output of more than 600 W near Earth and 300 W at Mars.

The cruise stage telecommunications system includes two X-band antennas; a low gain antenna (LGA) and a medium gain antenna (MGA). Both the solar array normal and the LGA and MGA are pointed in the direction of the spacecraft -Z axis which is aligned with the spacecraft spin axis. A key component of the X-band telecommunications system is the Small Deep Space Transponder (SDST) which supports two-way Doppler and ranging, command signal demodulation and detection, telemetry coding and modulation, and differential one-way range (DOR) tone generation (at ±19 MHz).

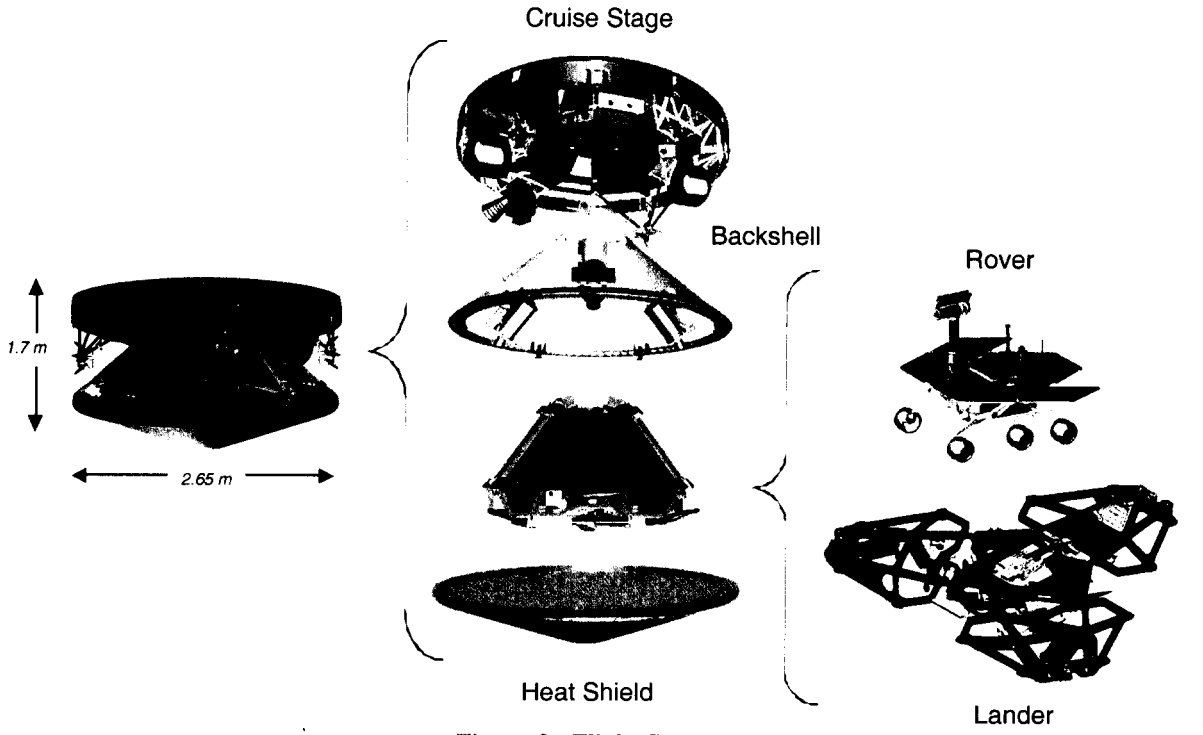


Figure 3: Flight System

Entry, Descent, and Landing (EDL) System

The MER aeroshell and parachute are based upon Mars Pathfinder and Viking heritage. The diameter of the parachute has been scaled up to approximately 15 m to accommodate the heavier MER entry mass. A Litton LN-200 Inertial Measurement Unit (IMU) mounted on the backshell is used (in conjunction with the rover IMU) to measure the deceleration of the vehicle in order to determine when to deploy the parachute. After the parachute is deployed the heatshield is released and the lander is deployed along a 20 m long zylon bridle which is stowed in one of the lander side petals.

A radar altimeter unit, whose antenna is mounted at one of the lower corners of the lander tetrahedron, is used to determine the distance to the Martian surface. The radar data are used to determine a firing solution for the Rocket Assisted Deceleration (RAD) system mounted on the inside of the backshell.

A soft landing is achieved by using the RAD rockets to slow the lander to zero vertical velocity at about 10-15 m from the surface. Since any tilt of the backshell off of vertical during the RAD rocket firing will impart a horizontal velocity - potentially increasing the overall landing velocity - a second rocket system is used to counteract this effect. The transverse impulse rocket system (TIRS) consists of three small solid rockets mounted radially in the backshell. These rockets can be fired in any combination to reduce the tilt of the backshell during RAD rocket firing. Figure 4 illustrates the major components of the aeroshell.

A Mars Pathfinder heritage airbag system is used to cushion the impact of the lander on the surface. The airbags are inflated to about 1.0 psig after a RAD rocket firing solution has been determined, but before the RAD or TIRS rockets fire. The airbags consist of a bladder that supports the pressure and several layers of vectran cloth (abrasion layers) to protect the bladder from sharp rocks that may be impacted.

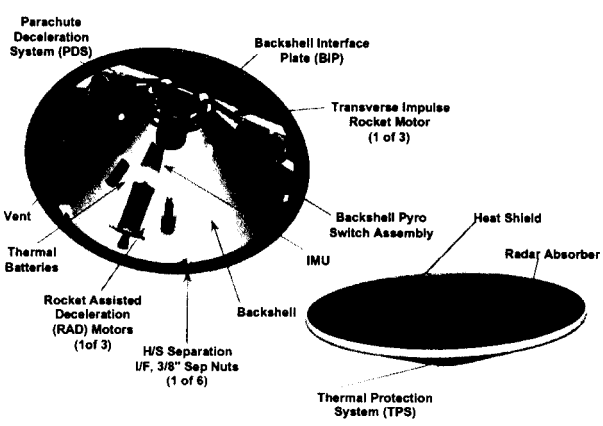


Figure 4: Aeroshell Configuration

Lander

The lander consists of a primary structure of four composite petals with Titanium fittings. The base petal connects to the three side petals through high torque lander petal actuators which can independently adjust the petals from the stowed (tetrahedron) configuration to the flat "iron cross" configuration as well as "hyper extending" the side petals below the plane of the base petal. The petals will initially be open to the iron cross position. The flight team may then command adjustment of the petals up or down to potentially improve the conditions for egress of the rover.

Egress aids or "ramplets" are connected between the side petals and are passively deployed when the petals are opened. These vectran cloth surfaces are supported by ribs and cables connected to the lander petals giving them some structural rigidity. When deployed they make the footprint of the lander approximately circular and provide additional egress directions by lowering the height of the "step" that the rover must take off of the lander to the surface of Mars. In addition, the egress aids cover potential obstacles including rocks and airbag material that hasn't been fully retracted. Figure 5 illustrates lander after the petals have been opened and the egress aids deployed.

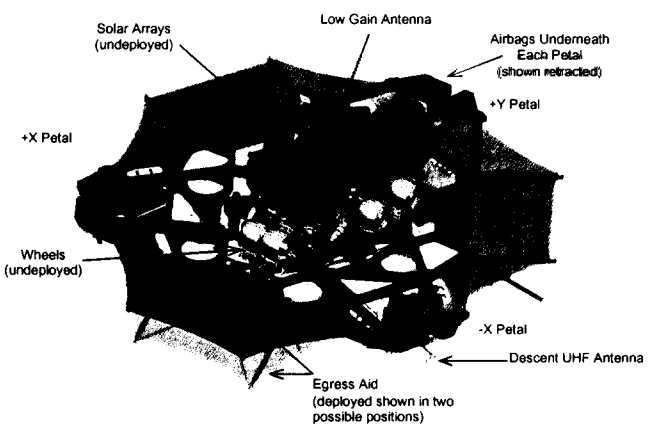


Figure 5: Rover Stowed on Lander

Rover

The MER rover is a 6-wheel drive, 4-wheel steered vehicle with a rocker-bogie suspension system similar in design to the Mars Pathfinder Sojourner rover, but substantially larger. When fully deployed, the wheelbase of the rover is approximately 1.4 m long and 1.2 m wide. At the height of the solar panel, the rover is 1.8 m wide by 1.7 m long and at the top of the Pancam Mast Assembly (PMA), the rover stands just over 1.5 m tall. The rover was designed with a ground clearance of 30 cm and can traverse obstacles of more than a wheel diameter (25 cm) in size. The rover has a top speed on flat hard ground of 5 cm/s, but under autonomous control with hazard avoidance achieves an average speed of about 1 cm/s.

In order for this large rover to fit within the Mars Pathfinder heritage lander volume, multiple deployments are needed. Initially the rover is stowed on the base petal of the lander in a configuration which allows the lander petals to fold into a tetrahedron around the rover. (The rover is shown in Figure 5 in its stowed configuration as it would appear just after the lander has opened its petals). Shortly after landing, the rover fires pyros that release tie-downs and allow the deployment of the rover solar panels, PMA, and high gain antenna (HGA). Following these deployments, tie-downs of the rover mobility system are released, and the rover is commanded to stand up and the front and rear wheels of the rocker-bogie mobility system are deployed and locked into position to prepare for egress. Figure 6 shows an illustration of the rover fully deployed on the surface of Mars.

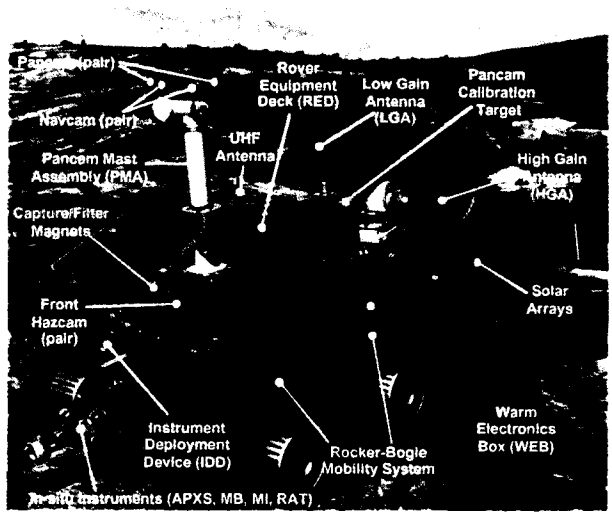


Figure 6: Rover in Deployed Configuration

The rover body and primary structure, called the Warm Electronics Box (WEB), is an exoskeleton of composite honeycomb lined with aerogel for insulation. The WEB houses all of the rover avionics including the flight computer, IMU, rechargeable batteries, and telecommunications hardware. Once on the surface of Mars, the rover is powered by a multi-panel, triple junction solar array. The array can produce nearly 900 Whr of energy per sol at the start of surface operations, but by the end of the 90 sol mission the energy generation capability has been reduced to about 560 Whr per sol due to the anticipated accumulation of dust on the solar arrays as well as the change in the season.

Science Payload

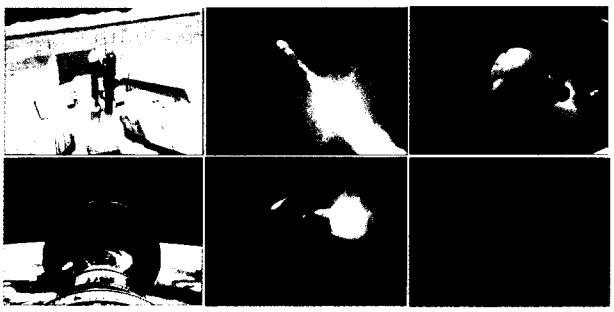
The Athena science payload is a suite of scientific instruments and tools for geologic exploration of the Martian surface that had its origins in the competitively selected payload that was to have flown on a Mars 2001 rover. The major elements of the payload are shown in Table 7.

Table 7: Mars Exploration Rover Instruments

Instrument	Location	Measurements / Operations
Panoramic Camera (Pancam) • a high-resolution stereo color panoramic imager	Stereo pair on Pancam Mast Assembly (PMA)	• 13 bands (430 to 980 nm) and one clear for far- and near-distance stereoscopic surface imaging • Blue and near-IR solar filters provide solar and sky imaging capability
Miniature Thermal Emission Spectrometer (Mini-TES) • a mid-infrared point spectrometer	Mirrors on PMA send light to instrument in Warm Electronics Box (WEB)	• 5 to 29 μm emission spectra of rocks and soils or atmosphere, thermophysical properties of surface
Microscopic Imager (MI) • Fine-scale monochromatic broadband imager with actuated dust cover and contact sensor	On Instrument Deployment Device (IDD)	• Close-up imaging of rock and soil targets
Mössbauer Spectrometer (MB) • in-situ ^{57}Co γ-ray source and a velocity drive, contact sensor	Sensor head on IDD, electronics in WEB	• Data for ground analysis of iron oxidation state and mineralogy of iron bearing phases, within target rocks and soils • 1.5 cm spot size • Sampling depth 200–300 μm
Alpha Particle X-Ray Spectrometer (APXS) • in-situ two-channel elemental chemical analyzer with contact sensor and dust door (calibration target on back of dust door)	Sensor head on IDD, electronics in WEB	• ^{244}Cm α-particle and X-ray source • Data for ground analysis of elemental chemistry of soils and rocks • Sampling depth 1–100 μm • 4.0 cm spot size
Rock Abrasion Tool (RAT) • 3-DOF mechanism; two actuated grinders, one axis forward/backward movement, contact sensor	On IDD	• Grinding tool which removes outer surface of rock to a depth of up to 5 mm over a spot of 45 mm in diameter • Exposing fresh material for characterization
Associated Instrument Hardware		
Magnet Arrays • Passive magnets for capturing magnetized particles	Capture and filter magnets on Rover Equipment Deck (RED)	• Collects magnetic particles from the Martian atmosphere for study by IDD-based instruments
	RAT magnets on RAT	• Separate magnetic particles from non-magnetic ones for Pancam viewing
	Sweep magnet on RED	
Compositional Calibration Target	On IDD structure underneath RED	• Magnetite-rich sample for Mössbauer calibration
Mini-TES External Calibration Target	On RED	• Radiometric calibration
Pancam Calibration Target • Plate with shadow post imaged by Pancam	On RED	• Pancam images illuminated and shadowed portions of PMA Target plate to measure sky brightness, from which atmospheric scattering properties are inferred

Mission Phases

Launch Phase



The Launch phase begins when the spacecraft transfers to internal power on the launch pad and ends when the spacecraft is declared stable, healthy, and the launch telemetry has been played back. The major activities in this mission phase include: the liftoff and ascent phase of the launch vehicle, insertion into a circular parking orbit, a coast period followed by additional launch vehicle burns necessary to inject the spacecraft onto a trajectory to Mars, separation of the spacecraft from the launch vehicle, initial acquisition by the DSN, and verification of the spacecraft's health.

The back-to-back launch period design for the MER-A and MER-B missions was developed to satisfy a number of competing requirements and constraints. These included trying to stay within the performance limits of the Delta II launch vehicles while maintaining line-of-sight visibility with Earth during EDL, accommodating various launch pad constraints, and trying to maintain a high probability of launching both spacecraft during their respective launch periods. In addition, other design goals, such as employing a constant arrival date for each MER mission in order to simplify operations, were key factors in the development of the overall launch period strategy.

Many of the important launch period design trades can be illustrated on the traditional mission design launch/arrival space or "pork-chop" plot. Figure 7 illustrates the launch/arrival space for the 2003 MER mission. The figure depicts contours of many of the important parameters that were considered in determining the baseline launch periods for the MER-A and MER-B missions such as: injection energy per unit mass (C_3), arrival V-infinity (V_∞) at Mars, Earth elevation at arrival, and local solar time at arrival. The placement of the two 18-day launch periods with constant arrival dates was designed to maximize the spacecraft injected mass (by minimizing launch vehicle injection energy requirements), ensure a minimum Earth elevation angle at landing plus 5 minutes of 10°, and provide a 21-day minimum separation between the arrival of MER-A and MER-B. In addition, the end of the MER-A launch period and the beginning of the MER-B launch period were separated by as much time as possible (8 days) in an attempt to accommodate a Delta II ground processing constraint which requires a minimum of 10 days separation between SLC-17A and SLC-17B pad launches. This separation helps to ensure a high probability of successfully launching both MER spacecraft within their respective launch periods.

In addition, to further increase the probability of launch, each launch day has two instantaneous launch opportunities corresponding to launch azimuths of 93° and 99°. These daily launch opportunities are separated by approximately 40-45 minutes.

In general, for any given launch azimuth, two distinct launch opportunities exist every day for a rocket to launch and inject its payload onto the proper Earth escape trajectory. The primary difference between these opportunities, usually referred to as the long coast and short coast opportunities, is the length of time that the launch vehicle must coast in the parking orbit before reaching the proper location to perform the Earth departure injection burn. Spacecraft power and post-injection geometry were the primary factors in choosing the short coast opportunity for MER-A and the long-coast opportunity for MER-B.

The Earth relative departure conditions that must be achieved by the Delta II launch vehicle in order to place the spacecraft onto an interplanetary trajectory to Mars are specified by defining the C_3, the declination of the departure or launch asymptote (DLA), and the right ascension of launch asymptote (RLA) at a specific time. The specific time is referred to as the targeting interface point (TIP) and is defined as 10 minutes after ignition of the third stage. The launch vehicle targets represent the conditions on the osculating departure hyperbola at the TIP. Table 8 indicates the launch vehicle targets for the open and close launch dates of the MER-A and MER-B launch periods.

Table 8: Launch Vehicle Targets

Launch Day	Launch Date	Launch Time (hh:mm:ss) (UTC)	Launch Vehicle Targets		
			C_3 (km^2/s^2)	DLA (deg) EME2000	RLA (deg) EME2000
MER-A: 93° launch azimuth, Mars arrival on January 4, 2004					
1	30 May 2003	18:28:38	9.33	2.13	352.79
18	16 June 2003	17:33:13	9.26	-4.12	344.09
MER-B: 93° launch azimuth, Mars arrival on January 25, 2004					
1	25 June 2003	04:34:47	10.39	2.59	340.29
18	12 July 2003	02:03:43	16.41	-5.18	333.60

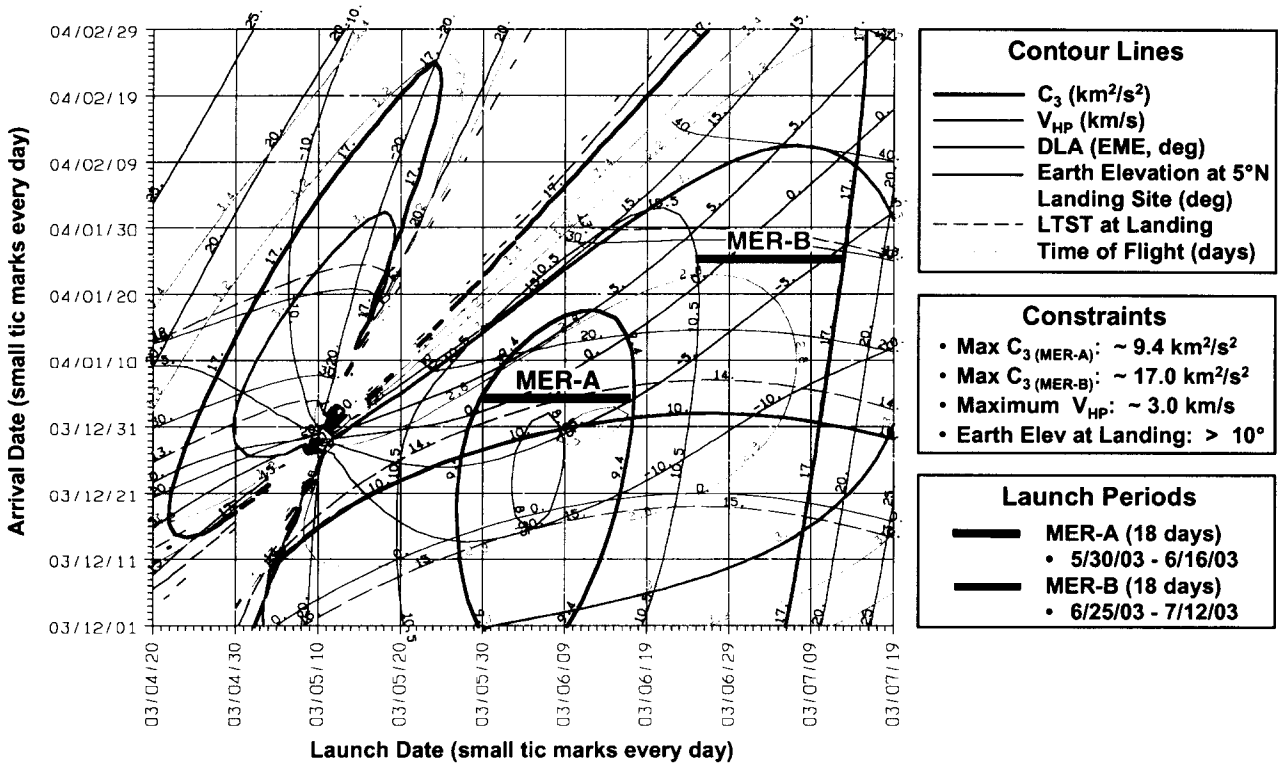


Figure 7: Launch / Arrival Space

Table 9 indicates the timing of the key launch vehicle events during the ascent and parking orbit portions of the launch trajectory for both the MER-A and MER-B missions (for the 93° launch azimuth only). Mission elapsed times are given in seconds from launch. Figure 8 illustrates the launch geometry for the MER-A open and MER-B open launch dates.

Table 9 also indicates the Deep Space Network (DSN) station rise and set times assuming a 10° station elevation mask. Given that MER-A uses the short coast and MER-B uses the long coast launch opportunity, initial acquisition of the spacecraft occurs at a different DSN complex. Initial acquisition of the MER-A spacecraft will take place at the Canberra complex in Australia, while initial acquisition of the MER-B spacecraft will occur at the Goldstone complex in California.

Following completion of the third stage burn, the spacecraft will separate from the launch vehicle upper stage. The separation event causes a breakwire to open, turning the spacecraft transmitter and propulsion drive electronics on. Spacecraft sun angles in the injection attitude provide safe power and thermal margins for both MER-A and MER-B for any launch date for over two weeks following injection.

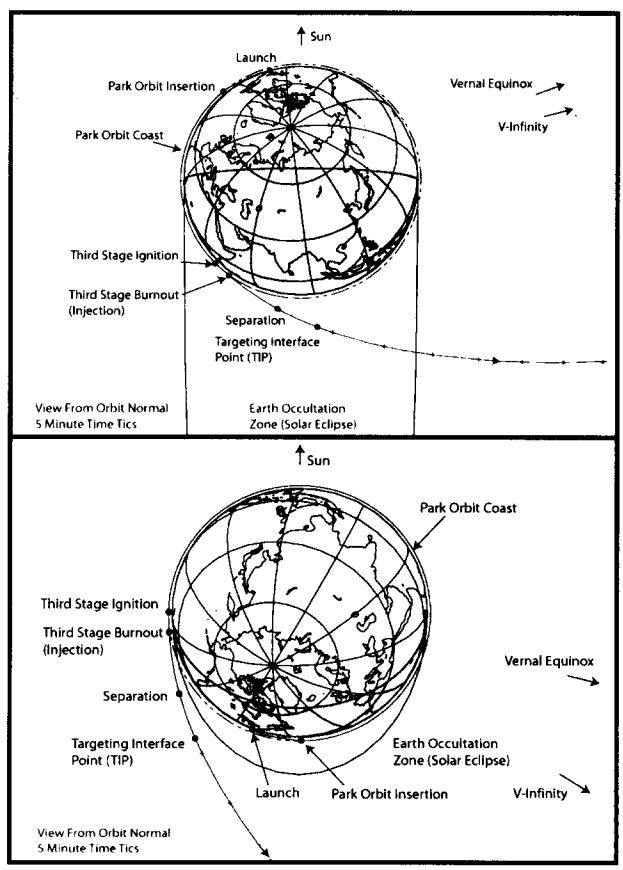


Figure 8: Launch Geometry

Table 9: Key Events During Launch Phase

	MER-A		MER-B	
	LP Open	LP Close	LP Open	LP Close
Launch Date	30 May 2003	16 June 2003	25 June 2003	12 July 2003
Coast Opportunity	Short		Long	
Launch Azimuth	93°		93°	
Launch Time (hh:mm:ss, UTC)	18:28:38	17:33:13	04:34:47	02:03:43
Event	**Mission Elapsed Time (sec)**		**Mission Elapsed Time (sec)**	
Liftoff	0.0	0.0	0.0	0.0
MECO	263.4	263.4	263.5	263.5
Stage II Ignition	276.9	276.9	277.0	277.0
Payload Fairing Jet.	298.5	298.5	297.0	297.0
SECO-1	579.7	579.7	526.0	526.0
Enter Solar Eclipse	1493.6	N/A	N/A	N/A
Exit Solar Eclipse	N/A	N/A	1523.4	2243.9
Restart Stage II	1755.3	1556.4	4219.0	4536.8
SECO-2	1873.9	1674.6	4357.7	4711.9
Enter Solar Eclipse	N/A	1684.9	N/A	N/A
Stage II-III Sep.	1926.9	1727.6	4410.7	4764.9
Stage III Ignition	1963.9	1764.6	4447.7	4801.9
TECO	2051.0	1851.7	4534.9	4889.0
Goldstone Rise	N/A	N/A	N/A	4996.3
S/C - Stage III Sep.	2338.9	2139.6	4822.7	5176.9
Goldstone Rise	N/A	N/A	4828.1	N/A
TIP	2563.9	2364.6	5047.7	5401.9
Canberra Rise	2959.9	2985.0	N/A	N/A
Exit Solar Eclipse	3144.0	3654.5	N/A	N/A
Canberra Set	25228.9	23295.0	N/A	N/A

MECO = Main Engine Cutoff
SECO = Second Stage Engine Cutoff
TECO = Third Stage Engine Cutoff

Cruise Phase

The Cruise phase begins soon after separation from the third stage of the Delta II launch vehicle when the spacecraft completes the Launch phase. The Cruise phase ends when the spacecraft is 45 days from entry into the Martian atmosphere. The duration of the Cruise phase is 5-6 months depending on the launch date for both MER-A and MER-B. The major activities during this phase include: checkout and maintenance of the spacecraft in its flight configuration, monitoring and characterization / calibration of the spacecraft and payload subsystems, attitude correction turns, navigation activities for determining and correcting the vehicle's flight path, and preparation for EDL and surface operations.

A plot of the MER-A and MER-B heliocentric trajectories are illustrated in Figure 9. Both MER missions follow a short, Type I interplanetary transfer trajectory to Mars. The Type I transfer trajectories are the fastest possible ballistic transits, with heliocentric transfer angles less than 180°. The plot also shows the locations of the six trajectory correction maneuvers (TCMs) which will be used to achieve the desired entry conditions at Mars. The first three TCMs occur during the Cruise phase and the last three occur during the Approach phase.

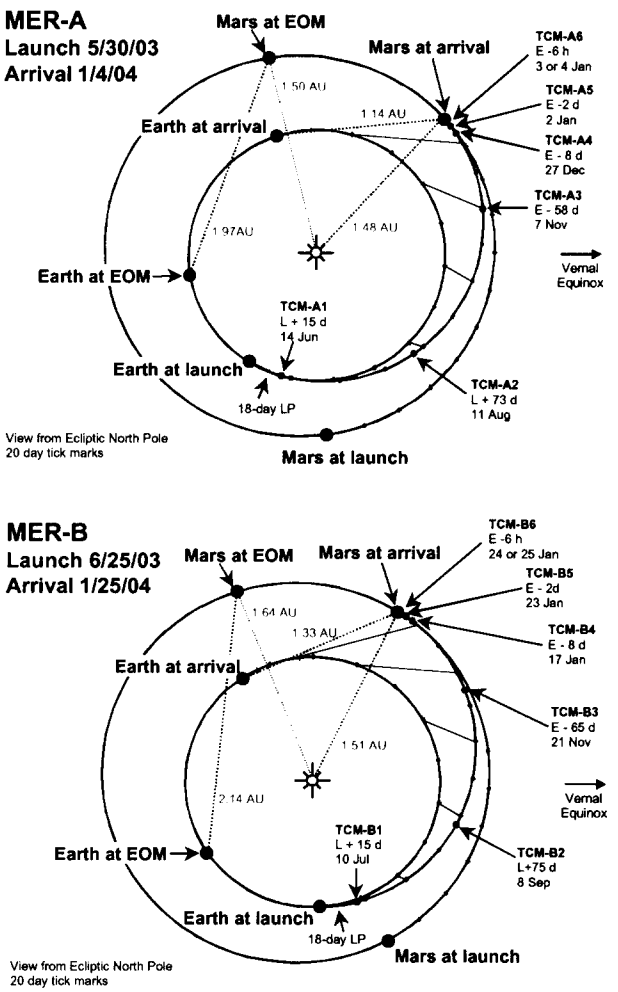


Figure 9: Interplanetary Trajectories

The launch vehicle will target the spacecraft toward an aimpoint that is biased away from Mars in order to achieve a probability of less than 10^{-4} that the third stage of the launch vehicle will impact Mars. (This is required to satisfy NASA's planetary protection requirements). The primary purpose of the first TCM, executed at Launch + 15 days, is not only to remove the injection bias and correct the launch vehicle injection

errors, but also to retarget to the desired landing site on Mars. Since the final landing site selection will not be made until just prior to launch, the retargeting aspect of TCM-1 is primarily used to adjust arrival time (i.e. longitude) at Mars in order to land at the desired landing site. The second and third TCMs are each used to correct the execution errors from the previous maneuvers and to target to the final atmospheric entry conditions.

The MER spacecraft is capable of performing a trajectory correction maneuver in a number of different ways. It can execute a maneuver from the attitude that it is in at the time of the maneuver or it can turn to a different attitude (or combination of attitudes) to fire the thrusters and execute the maneuver. A ΔV imparted along the direction of the spin axis of the cruise stage (either along the +Z or -Z axis) is called an axial burn and can be executed as a single, continuous burn. A ΔV imparted normal to the spin axis is called a lateral burn and is implemented by pulsing the thrusters in each cluster once per spacecraft revolution. In the most general sense, a ΔV can be achieved by performing a turn and pure axial, a turn and pure lateral burn, or as a vector sum of a combination of two ΔV components (called a vector mode maneuver).

Since the spacecraft ΔV and propellant requirements are dominated by TCM-1, it could be quite costly to execute TCM-1 as a vector mode manevuer. As a result, the MER project is prepared to use any of the available maneuver modes to execute TCM-1. The remainder of the TCMs will be performed in vector mode in order to avoid any trajectory perturbations that might be introduced by turning the spacecraft. Table 10 indicates a breakdown of the total mission ΔV and propellant requirements for the most demanding launch dates within the MER-A and MER-B launch periods.[1] Propellant for both TCMs and attitude control are included.

During the interplanetary flight to Mars, the MER cruise stage is spin-stabilized with a nominal spin rate of 2 rpm. As a result, periodic spin axis pointing updates will be required to maintain communications with Earth and to ensure adequate solar illumination of the cruise stage solar panels for power as the relative positions of the Earth and Sun change during flight. During the early part of the Cruise phase, when the Sun-Spacecraft-Earth angle or Sun-Probe-Earth (SPE) angle is large (up to 100°), the attitude strategy is to point the spacecraft -Z axis in between the direction to the Earth and the Sun. During this period, communications with the Earth are via the spacecraft LGA which does not require tight pointing towards

Table 10: Mission ΔV and Propellant Requirements

	MER-A	MER-B
	LP Open (5/30/03)	LP Close (7/12/03)
TCM-1 ΔV_{mean} / ΔV_{99} (m/s)	32.8 / 79.5	34.0 / 68.0
TCM-2 ΔV_{mean} / ΔV_{99} (m/s)	1.5 / 5.5	1.7 / 5.7
TCM-3 ΔV_{mean} / ΔV_{99} (m/s)	0.2 / 0.6	0.1 / 0.5
TCM-4 ΔV_{mean} / ΔV_{99} (m/s)	0.2 / 0.4	0.2 / 0.4
TCM-5 ΔV_{mean} / ΔV_{99} (m/s)	0.1 / 0.2	0.1 / 0.2
TCM-6 ΔV_{mean} / ΔV_{99} (m/s)	0.6 / 1.3	0.6 / 1.4
Total ΔV_{99} (m/s)	**83.0**	**72.8**
TCM Propellant $Mass_{99}$ (kg)	39.8	35.0
ACS Propellant $Mass_{99}$ (kg)	3.0	3.0
Total Propellant $Mass_{99}$ (kg)	**42.8**	**38.0**
Propellant Allocation (kg)	47.0	47.0
Propellant Margin (kg)	**4.2**	**9.0**

- ΔV_{mean} and ΔV_{99} are the estimated ΔVs at mean and 99% confidence levels. $Mass_{99}$ represents the propellant mass at the 99% confidence level.
- The value for Attitude Control System (ACS) propellant represents effect of combining TCM and ACS distributions.
- Results assume TCM-5 does not occur and TCM-6 does.

Earth. After a couple of months, when the SPE angle has decreased to below about 30°, the attitude maintenance strategy changes to one in which the spacecraft -Z axis is maintained within ±8° of Earth. A short time later, communications with Earth are switched from the spacecraft LGA to the MGA. The MGA is used for the remainder of the interplanetary cruise to Mars.

A total of about a dozen attitude maintenance turns will be required during the 7 month cruise to Mars. As the spacecraft gets farther from the Sun, sufficient power is maintained not only by periodic attitude updates, but by bringing more sections of the cruise stage solar array on-line.

Approach Phase

The Approach phase is defined as the period of time prior to arrival at Mars that is dedicated solely to the activities necessary to ensure a successful Entry, Descent, and Landing (EDL). The phase begins when the spacecraft is 45 days from entry into the Martian atmosphere and ends when the spacecraft reaches the atmospheric entry interface point; a point defined to occur at a radius of 3522.2 km from the center of Mars. The principal activities during this phase include the acquisition and processing of navigation data needed to support the development of the final three trajectory correction maneuvers (TCMs) and the spacecraft activities leading up to the final turn to the entry attitude and separation from the cruise stage. All other spacecraft activities, particularly those that could

influence the spacecraft's trajectory (such as spacecraft attitude turns), are minimized. During the Approach phase, the amount of requested DSN tracking is substantially increased to allow more accurate trajectory solutions to be determined in the final weeks before arrival at Mars.

The last three TCMs are used to perform final adjustments to the incoming trajectory at Mars to ensure that the desired entry conditions are achieved. Table 11 indicates a brief description of each maneuver and the planned date for its execution.

Table 11: Approach Phase TCMs

TCM	MER-A Date	MER-B Date	Description
TCM-4	27 December 2003 (Entry – 8 days)	17 January 2004 (Entry – 8 days)	Correct TCM-3 errors; target to entry aimpoint
TCM-5	2 January 2004 (Entry – 2 days)	23 January 2004 (Entry – 2 days)	Correct TCM-4 errors; final entry targeting maneuver required for site safety
TCM-6	4 January 2004 Entry – 6 hours	25 January 2004 Entry – 6 hours	Final entry targeting maneuver opportunity

The delivery accuracy requirements for MER are much tighter than previous missions in order to ensure not only the safety and robustness of the flight system during atmospheric entry and descent, but also the safety of the vehicle upon impact with the ground. Smaller delivery errors result in smaller landing ellipses on the surface, which in turn make it easier to select safe, but also scientifically interesting sites.

Previous missions have relied almost exclusively on the use of two-way Doppler and range data to navigate their way to Mars. The MER mission, however, has taken advantage of the development of a new and improved ΔVLBI (Delta Very Long Baseline Interferometry) system within the DSN. ΔVLBI refers to a generic form of interferometric observations of a spacecraft using pairs of DSN stations. The specific form of ΔVLBI that MER will use is called ΔDOR (Delta Differential One-Way Range). In a ΔDOR measurement, two DSN stations at different sites are used to simultaneously observe a spacecraft followed by simultaneous observations of a reference radio source. From this type of measurement, the angular separation between the spacecraft and the radio source can be determined. By augmenting the traditional line-of-sight navigation measurements with angular, plane-of-sky measurements, delivery errors at Mars can be significantly reduced. As a result, the MER mission has baselined an intensive campaign of ΔDOR measurements in order to meet the stringent entry flight path angle (FPA) delivery requirements. For all of the landing sites currently under consideration, the entry FPA delivery uncertainties are all less than or equal to ±0.25° (3σ) about a nominal inertial entry FPA of -11.5° assuming a final TCM at Entry - 2 days. Table 12 presents the navigation delivery accuracies for TCMs 4, 5, and 6 for selected landing sites for MER-A and MER-B.[2]

Table 12: Delivery Accuracy for Selected Sites

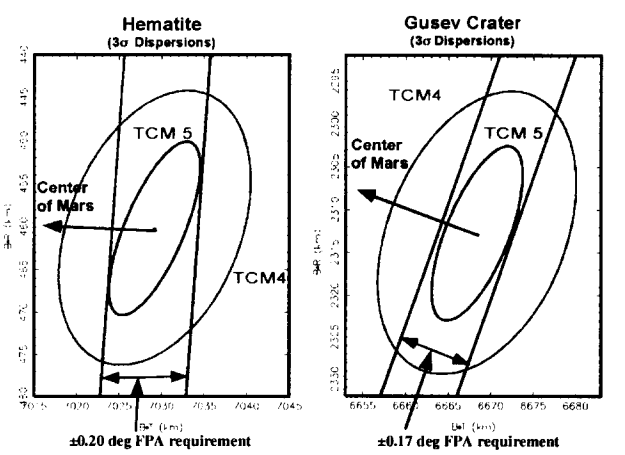
	MER-A		MER-B	
Landing Site	**Isidis Planitia**	**Gusev Crater**	**Isidis Planitia**	**Hematite**
Day of Launch Period	Open	Open	Open	Open
Landing Site Latitude †	4.62° N	14.67° S	4.55° N	1.98° S
Landing Site Longitude †	85.21° E	175.75° E	84.01° E	353.82° E
Flight Path Angle Target	**-11.5 deg**		**-11.5 deg**	
Flight Path Angle Req't (3σ)	**±0.25 deg**	**±0.17 deg**	**±0.25 deg**	**±0.20 deg**
B-plane Angle	**-4.3 deg**	**19.1 deg**	**-6.0 deg**	**1.9 deg**
TCM-4 Delivery (3σ) @ Entry - 8 days:				
Semi-major Axis	17.6 km	17.4 km	17.4 km	17.5 km
Semi-minor Axis	10.4 km	10.4 km	9.5 km	9.7 km
Ellipse Orientation Angle	113.0 deg	112.0 deg	110.0 deg	109.6 deg
B Magnitude	12.3 km	10.4 km	11.4 km	10.7 km
Flight Path Angle (3σ)		**±0.41 deg**		**±0.43 deg**
TCM-5 Delivery (3σ) @ Entry - 2 days:				
Semi-major Axis	11.0 km	10.8 km	11.0 km	10.3 km
Semi-minor Axis	3.4 km	3.3 km	2.6 km	2.6 km
Ellipse Orientation Angle	111.0 deg	112.0 deg	110.0 deg	107.6 deg
B Magnitude	5.6 km	3.3 km	5.4 km	3.8 km
Flight Path Angle (3σ)		**±0.13 deg**		**±0.15 deg**
TCM-6 Delivery (3σ) @ Entry - 6 hours: **				
Semi-major Axis	7.9 km	7.5 km	8.0 km	7.3 km
Semi-minor Axis	0.8 km	0.8 km	0.7 km	0.6 km
Ellipse Orientation Angle	120.0 deg	119.0 deg	116.0 deg	115.5 deg
B Magnitude	4.5 km	1.5 km	4.2 km	3.0 km
Flight Path Angle (3σ)		**±0.06 deg**		**±0.12 deg**

† Site locations assumed for Navigation analysis.

* Nav analysis assumed 1 ΔDOR measurement every other day during final week prior to landing.

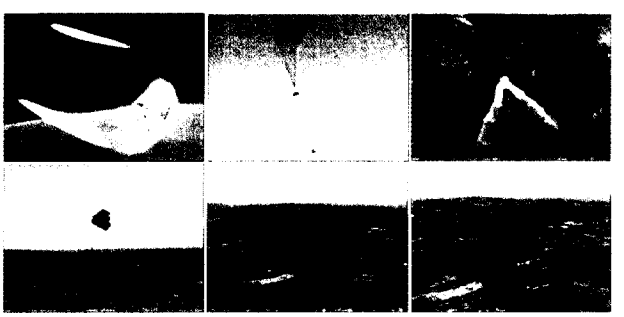
** TCM-6 results assume that TCM-5 does not occur.

Maximum FPA Error



After TCM-4, a specific piece of flight software, called the "EDL behavior", is initiated. This code is designed to autonomously control the spacecraft during EDL. The first action taken by the EDL behavior occurs approximately 2 hours prior to entry. At 70 minutes prior to entry the spacecraft turns to the proper entry attitude. This attitude significantly increases the off point angles to both the Sun and the Earth affecting both power and communications. Fifty seconds prior to cruise stage separation, the on-board X-Band telecommunications system starts to send signal tones (referred to as Multiple Frequency Shift Key tones or M-FSK tones) to the ground. The M-FSK tones are coded to indicate the spacecraft state and the completion of critical EDL events. At 15 minutes prior to entry the cruise stage is jettisoned and the entry vehicle becomes dependent on batteries for the remainder of the entry sequence. After separation from the cruise stage, the entry vehicle transmits M-FSK tones via a LGA on the backshell that emerged from inside the jettisoned cruise stage LGA. The entry vehicle, containing the rover, is protected during entry by the heatshield and the backshell. The cruise stage, however, is unprotected and burns up following the entry vehicle into the Martian atmosphere.

EDL Phase



The MER Entry, Descent, and Landing (EDL) phase is defined to begin when the spacecraft reaches the Mars atmospheric entry interface point; a point 3522.2 km from the center of Mars, and ends with the lander on the surface of Mars in a thermally stable, positive energy balance, commandable configuration after the rover has completed its critical deployments. By convention, the landing sol is known as Sol 1.

The MER EDL design is an adaptation of the approach used for the Mars Pathfinder mission in 1997. The design employs an aeroshell and a parachute to decelerate the lander through the Martian atmosphere. The parachute is deployed after approximately four minutes of atmospheric deceleration, at an altitude of about 8.5 km above the surface with a Mach number of about 1.8, a dynamic pressure of about 700 N/m^2, and an atmospheric relative velocity of about 425 m/s. Twenty seconds after the parachute is deployed the heatshield is released and 10 seconds later the lander separates from the backshell and begins to deploy along a 20 m long bridle. Once the bridle is fully deployed the radar altimeter system is turned on and begins taking measurements. Radar acquisition of the ground will occur within about 2.4 km of the surface, approximately 5 minutes after entry and only about 30 seconds before landing, with the system traveling at about 75 m/s. At 8 seconds before touchdown, the lander airbags are inflated allowing the airbags to warm before impact. The retro-rockets are then ignited 2 seconds later. After its initial impact, the lander will bounce along the Martian surface until it rolls to a stop. The airbags are then deflated and retracted, and the lander petals and egress aids are deployed. Once the petals have opened, the rover deploys its solar arrays and begins preparations for egress from the lander.

Figure 10 illustrates the nominal EDL sequence of events. The data are presented for landing at the highest elevation landing site (Hematite) which has a surface elevation of approximately -1.3 km relative to the reference standard determined by the MOLA instrument (the Mars Orbiter Laser Altimeter) on board the Mars Global Surveyor (MGS) spacecraft. The MER-A event times are listed first with the MER-B times are listed in parentheses.

Since visibility into the performance of the EDL system is critically important to both the MER project and to NASA, a posigrade, daytime entry was selected in order to allow the EDL events to be directly visible from Earth. Table 13 indicates some of the key characteristics of the MER-A and MER-B arrival trajectories as well as the geometry after landing across the full range of possible landing site latitudes for both MER missions. The table indicates, for example, that MER-A lands at approximately 2:00 p.m. local time on Mars and that Earth set can occur within an hour after landing, whereas MER-B lands at around 1:15 p.m. local time and it can be nearly two and a half hours between landing and Earth set.

Figure 10 also indicates that the on-board X-band system will be transmitting M-FSK tones direct-to-Earth (DTE) throughout the EDL phase. The X-band signal, however, is expected to be intermittent during the period when the lander is suspended on the bridle due to swinging motion of the lander on the bridle during descent. The rover LGA, which emerged from inside the backshell LGA, is used to radiate from the top of the lander once the lander is separated from the backshell.

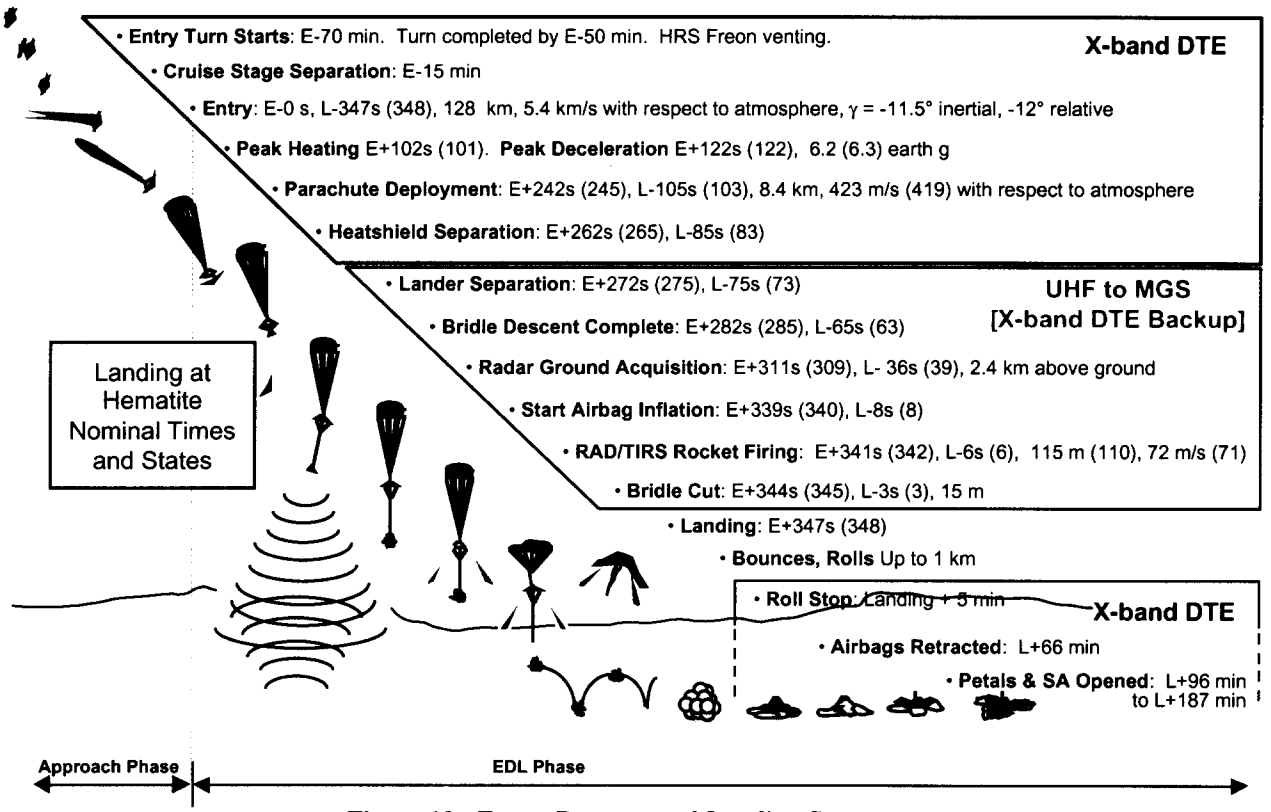


Figure 10: Entry, Descent, and Landing Sequence

Table 13: Arrival Characteristics and Landing Geometry

Arrival Characteristics

Mission	Case	Launch Date (2003)	Arrival Date (2004)	Landing Site Latitude Range	V_∞ (km/s)	Atmos.-Relative Entry Velocity (km/s)	Earth Range (AU)	Sun Range (AU)	Ls (deg)	Sun Declination (deg) (MME)	Earth Declination (deg) (MME)
MER-A	Open	May 30	Jan 4	14.6°S→4.2°N	2.77	5.42	1.14	1.48	327.7	–13.2	–25.4
	Close	June 16			2.70	5.40					
MER-B	Open	June 25	Jan 25	2.1°S→ 14.3°N	2.83	5.44	1.33	1.51	339.0	–8.8	–23.2
	Close	July 12			2.89	5.47					

Landing Geometry

Mission	Case	Launch Date (2003)	Arrival Date (2004)	Landing Site Latitude Range	Time at Landing LTST (UTC)		Earth Elevation at Landing (deg)		Time from Landing to Earth Set (0°) (hh:mm)	
					Gusev	Isidis	Gusev	Isidis	Gusev	Isidis
MER-A	Open	May 30	Jan 4	14.6°S→4.2°N	14:00 (04:09)	13:51 (09:58)	22.0	16.0	1:42	1:14
	Close	June 16			14:20 (04:30)	14:17 (10:15)	17.5	12.3	1:21	0:57
					Hematite	Elysium	Hematite	Elysium	Hematite	Elysium
MER-B	Open	June 25	Jan 25	2.1°S→ 14.3°N	13:12 (04:56)	13:16 (21:21)	30.9	22.0	2:19	1:46
	Close	July 12			13:08 (04:53)	13:08 (21:12)	31.6	23.7	2:22	1:54

Posigrade Entry, Inertial Flight Path Angle = –11.5 deg, Atmospheric Entry Interface Radius = 3522.2 km
Ls = areocentric longitude of the Sun (i.e. a measure of the Martian seasons), LTST = Local True Solar Time

In addition to the X-band system, a separate UHF system will provide an alternate data return path for critical EDL data which may be needed to reconstruct a fault should one occur. Following lander separation, a small monopole, UHF antenna mounted at the top of the lander tetrahedron will be deployed to communicate with the Mars Global Surveyor (MGS) spacecraft at 8 kb/s providing engineering telemetry that can be relayed to Earth at a later time.

Through incredible good luck, the current MGS orbit plane happens to be well positioned to cover the EDL events of both MER-A and MER-B. Only a couple of very small in-plane, orbit phasing maneuvers will be required to place the MGS spacecraft over the MER landing sites at the proper times. Figure 11 illustrates the arrival geometry of the MER-A and MER-B approach trajectories relative to the spacecraft expected to be in orbit about Mars at the time of landing.

Monte Carlo analyses of EDL trajectories, including effects of navigation delivery dispersions and atmospheric and aerodynamic uncertainties, have been used to determine landing scatters at each of the primary landing sites, for the open and close of the launch periods. Margins have been added to account for other effects such as sustained winds, additional atmospheric density uncertainties, distance traveled from impact to roll stop, and cross-track control uncertainty. In addition, margin has been added to allow for the possibility of shallowing the targeted entry flight path angle to increase the time between parachute deployment and landing (and to possibly reduce entry loads). Overall, landing ellipses are largest at the northern end of the latitude band and smallest at the southern end, varying roughly linearly in between. The range of landing ellipse dimensions for the northern and southern most landing sites for MER-A and MER-B are shown in Table 14. All site ellipses are based on navigation delivery uncertainties assuming TCM-5 at Entry – 2 days.

MER-A Approach / EDL Geometry

Launch 5/30/03
Arrival 1/4/04

MER-B Approach / EDL Geometry

Launch 6/25/03
Arrival 1/25/04

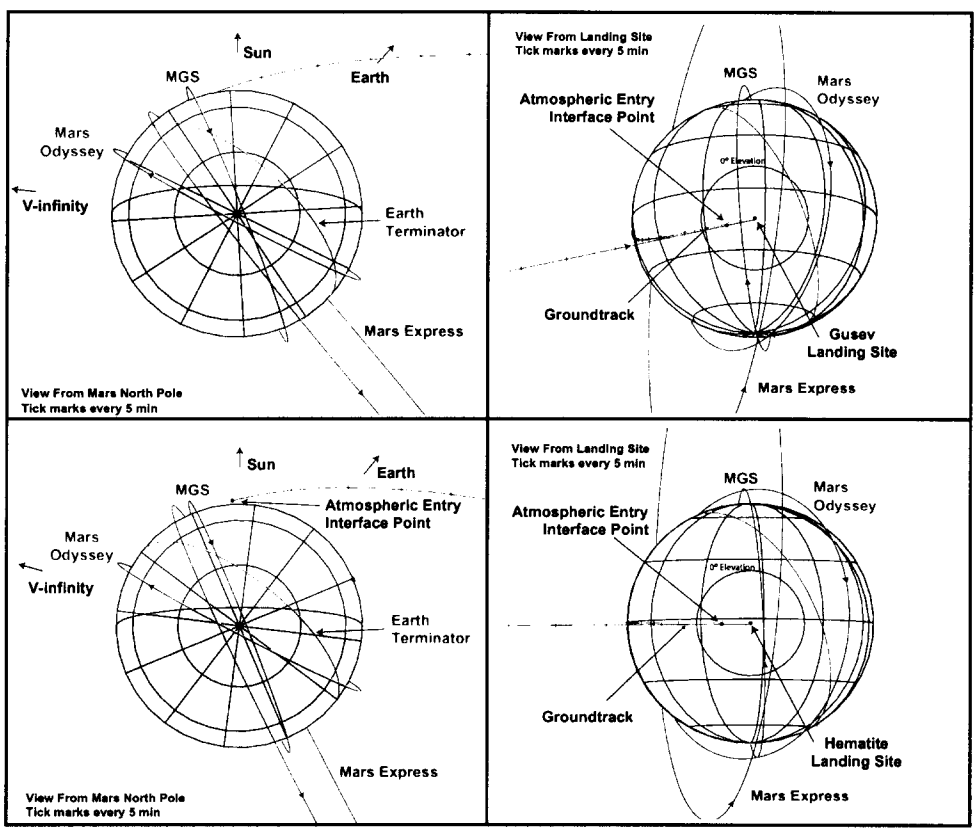


Figure 11: Approach / EDL Geometry

Table 14: Landing Ellipse Size / Orientation

Mission	Landing Site Region	99% Landing Ellipse		Major Axis Azimuth with respect to true North (deg)
		Major Axis (km)	Minor Axis (km)	
		Open/Close	Open/Close	Open/Close
MER-A	Gusev	96 / 103	19 / 19	76 / 74
	Isidis	132 / 127	16 / 17	88 / 85
MER-B	Hematite	117 / 112	18 / 19	86 / 82
	Elysium 2 *	165	15	95

* Landing ellipse data for the Elysium site are only approximate.

As a representative example, Figure 12 illustrates the MER-A landing ellipse overlaid onto a topographic map of the Gusev Crater landing site. The thin vertical, black-and-white strips in the middle of the crater are the high resolution images of the landing site region taken by the Mars Orbiter Camera (MOC) on-board the MGS spacecraft.

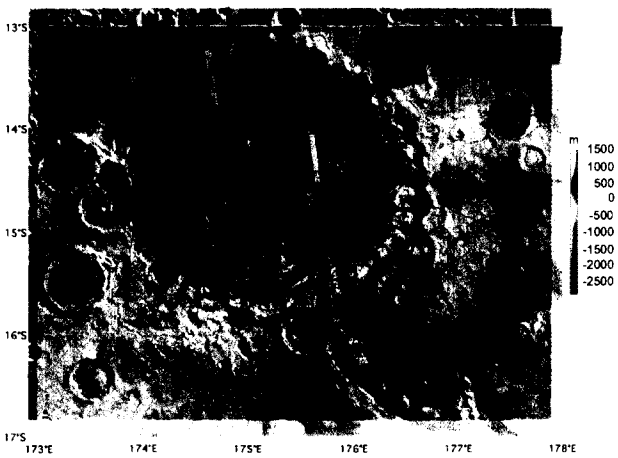
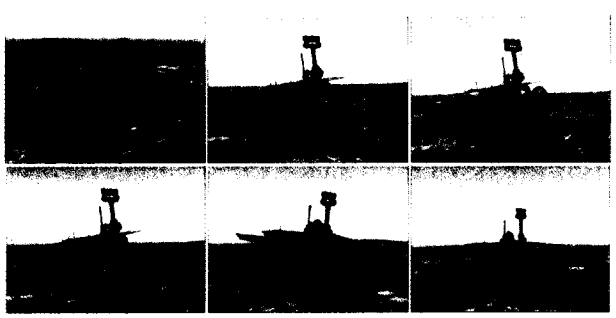


Figure 12: Topographic Map of Gusev Crater

Post-Landing Through Egress Phase



The Post-Landing Through Egress phase is defined to begin after the rover has been placed in a thermally stable, positive energy balance, commandable "safe state" after landing. The phase ends with the X-band transmission confirming that the rover's six wheels are on the surface Mars. The phase includes all of the activities required for the rover to transition to lander-independent operations on the surface of Mars. The principal activities during this phase include the non-critical Sol 1 deployments, characterization of the landing site and surrounding terrain, rover stand-up, a science instrument calibration campaign, the selection of a suitable egress path, and finally egress from the lander onto the Martian surface.

Due to the limited a priori knowledge of the terrain at the landing site, the flight team must interactively assess the rover data, command the rover, and then assess the resulting data before proceeding to subsequent steps. Consequently, many possible egress scenarios exist. The rate at which the post-landing through egress activities can proceed is largely dictated by the availability of power, the duration and number of ground decision points, and the availability of a communications link.

The last act of the EDL behavior is to initiate the non-critical Sol 1 deployments, including the Pancam Mast Assembly (PMA) and the HGA. Only after PMA is deployed can a visual survey of the rover and the surrounding area be performed in preparation for the ground-directed adjustments leading up to rover egress. The lander is imaged using the Hazcams. These images provide data from which the step off height from the lander to the Martian surface can be determined. Navcam and Pancam panoramas are then taken. The Navcam image provides information regarding the deployment of the egress aids, the height of the lander above the terrain, and the availability of viable egress paths from the lander. Both the Navcam and Hazcam images are used to assess the presence of airbag material or other debris on the lander petals. Once the images have been taken, the HGA is deployed in anticipation of the first high-rate X-band telemetry pass on Sol 2. This is followed by a determination of the Sun's position using the Pancam. The rover is then shutdown until the next available UHF pass during which the EDL and deployment data are retransmitted.

The next major step continues with the characterization of the terrain beneath and surrounding the lander by performing a petal articulation test. In this test, the lander petals are moved, IMU data are collected, and Navcam images of the areas between the petals are taken. If the data indicate that the terrain beneath the lander is sufficiently stable to allow deployment of the rover mobility system, the rover proceeds with an automated rover standup sequence.

The automated standup sequence guides the deployment of the rover rocker-bogie mobility system. In this sequence, a rover lift mechanism lifts the rover allowing the rockers (front wheels) to be deployed. The lift mechanism then lowers the rover, and the bogies (rear wheels) are deployed. Hazcam images are collected throughout this process to provide diagnostic data.

Once the rover standup sequence is completed, the lander petals are adjusted to their final egress configurations. The lander's connection to the rover is then cut, and the rover is commanded to turn to the identified egress direction. As the final step, the rover drives off of the lander deck onto the surface of Mars.

The major deployment and egress activities are power intensive and must occur during the Mars day when the solar arrays can charge the rover battery, and when the rover and the landing site are naturally illuminated. Unlike in cruise, when the communications link to Earth was continuous, the rover's transmitter is off much of the time to conserve energy. High-rate X-band direct-to-Earth (DTE) communications links are available only after the HGA has been deployed and then are limited by thermal and power constraints to only a few hours per sol.

Throughout the Post-Landing Through Egress phase, a go/no-go command strategy is adopted. This strategy involves downlinking the data from the rover, quickly assessing whether or not data meet the criteria for a given decision point, then uplinking a sequence of commands 90 minutes later for the rover to execute. If the criteria for a given decision point are met, the process progresses to the next step. If the criteria are not met, then the activity is repeated or modified until the criteria are met. An overview of the decision tree showing the various decision points is provided in Figure 13.

In conjunction with the engineering activities supporting egress of the rover from the lander, a number of important science calibrations are also performed during the Post-Landing Through Egress phase. Some of the measurements function as post-landing health checks while other measurements serve as early baseline measurements that need to be taken before dust accumulates on the calibration targets or magnets. In addition, after rover standup, but prior to egress from the rover, the Pancam and Mini-TES instruments acquire 360° panoramic images of the landing site. These activities are referred to as the "mission success panoramas" because their acquisition may result in partial fulfillment of the mission success criteria.

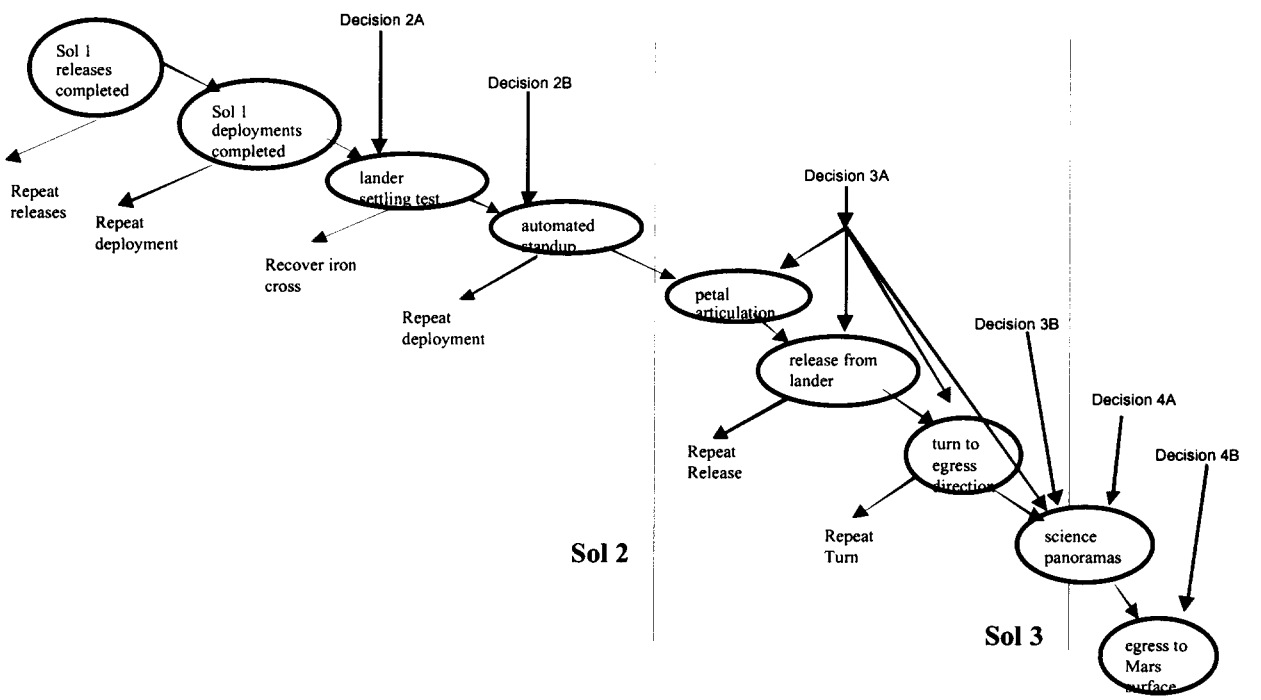


Figure 13: Post-Landing Through Egress Decision Tree

Surface Operations Phase

The Surface Operations phase begins with completion of the first X-band direct-to-Earth (DTE) communications link following the rover's successful egress off of the lander. The surface mission will continue through Sol 91 (90 sols after the landing sol; approximately 93 Earth days from landing), which is the defined End-of-Mission (EOM). The design of the Surface Operations phase is subject to several mission engineering constraints, including those imposed by the planetary geometry, the dust and thermal environment, the availability of the Mars orbiting assets, and the availability of DSN resources. These constraints determine the rover energy availability, thermal margins, and data downlink capability.

Throughout both of the MER-A and MER-B surface missions, the Mars–Sun range and the Mars–Earth range steadily increase. Consequently, both power and telecom resources decrease over the surface mission, resulting in steadily declining energy availability and data return capability. In addition, as the average daily temperature drops, an increasing share of the available rover energy must be devoted to thermal survival, leaving a further decreasing amount of energy available for performing rover science activities.

Since the range to Earth nearly doubles over the period from MER-A landing through MER-B EOM, the corresponding data rate capability to Earth drops by nearly a factor of four. The expected data rates using the HGA range from approximately 12 kb/s early in the MER-A mission to about 3.5 kb/s at the end of the MER-B mission. The rover LGA data rate capability within 20 degrees of the LGA boresight (almost three hours centered around local noon on the Mars surface) ranges from 300 b/s down to 40 b/s over the same time period. The rates quoted above assume a 70m DSN antenna, use of 15, 1/6 convolutional encoding (rate 1/6 with constraint length 15), and adverse link tolerances. The MER project can use a less powerful 7, 1/2 convolutional encoding scheme in the event that the decoders required to use the 15, 1/6 code at the DSN stations are unavailable (possibly allocated to another spacecraft). Use of the less powerful encoding scheme would result in approximately a 35% reduction in data rate capability.

A Sol in the Life of the Rover Mission

A representative sol in the life of the rover mission is illustrated in Figure 14. Since the rover is solar-powered, the majority of the rover's activities occur between sunrise and sunset. Rover communications are determined by when the Earth is in view and when orbiter overflights make UHF relays possible.

A typical rover day starts with the morning wake up. Wake up is typically triggered by an on-board alarm clock, but can also be triggered when there is sufficient power coming out of the solar arrays to power the avionics. Typical morning activities include executing sequenced commands sent the previous day and preparing for the morning X-band communications pass. Commands for the remainder of the current sol and the next sol are uplinked during the morning X-band pass. This communications pass may or may not also involve the rover sending telemetry back to Earth. At the end of the morning communications pass, a new "master sequence" is activated. If for any reason a new master sequence is not started, the previous master sequence will continue operating the rover for another sol. This part of the sequence is known as the "runout" sequence. At the end of the morning activities, the master sequence may issue a "shutdown and resume" command, which would shut down the rover and also set the rover alarm clock with the next time to wake up and resume the master sequence.

During the afternoon, the rover also has an X-band communications pass. The purpose of this pass, however, is the opposite of the morning pass in that it is primarily a downlink opportunity. During the afternoon pass, data required for planning the next sol (referred to as "critical data") are downlinked to Earth. Receipt of these data starts the next sol's sequence development cycle.

Non-critical science and engineering telemetry is relayed to Earth via the Mars Odyssey and MGS orbiters. The data are sent from the surface to the orbiters via a UHF link. Given the Mars Odyssey and MGS orbits, UHF data relay opportunities occur up to two times per sol per orbiting asset. The UHF passes range in duration from about 2 to 17 minutes and are distributed between approximately midnight and sunrise and from midday to late afternoon (see Figure 14). It is anticipated that over 60% of the total mission data return will be returned via the UHF relay channel.

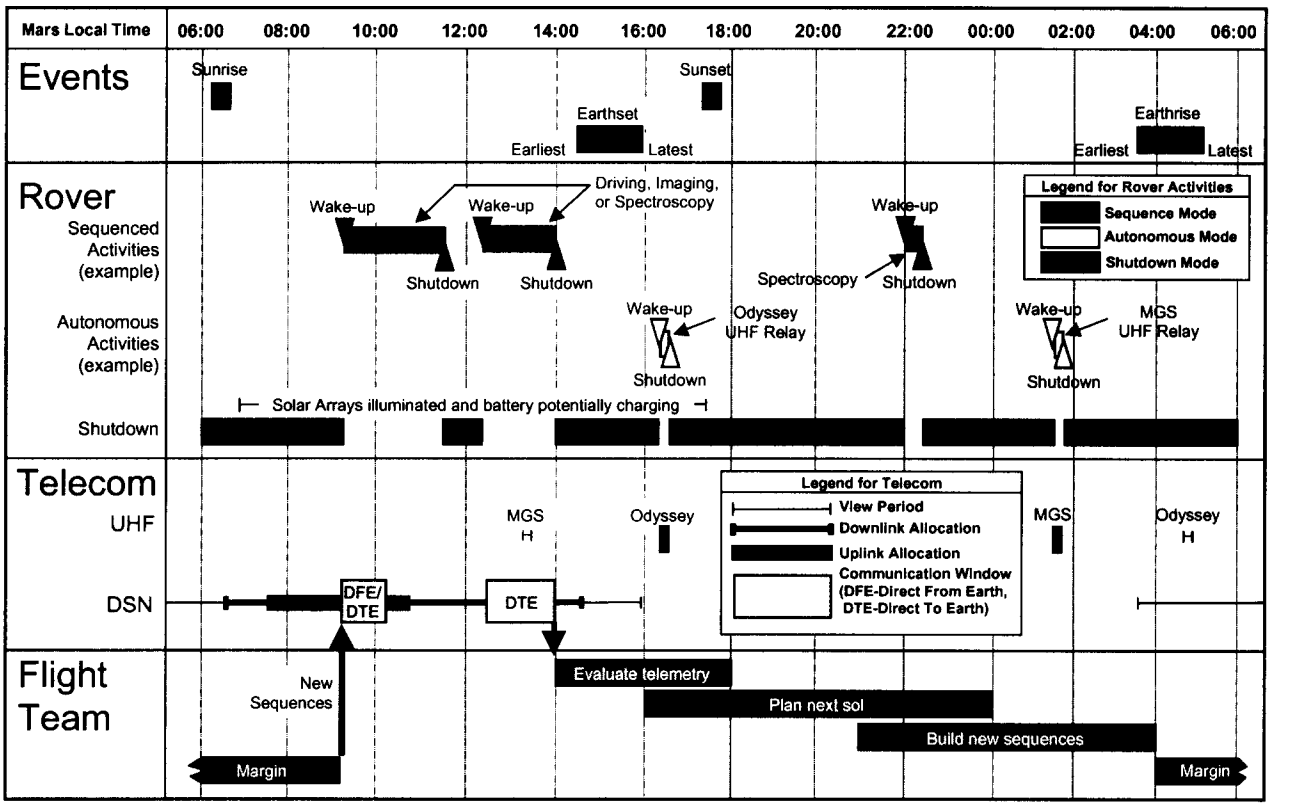


Figure 14: Representative Sol in the Life of the Rover

The downlink process consists of telemetry evaluation and the uplink process consists of activity planning for the next sol, sequence building, and transmission of the command load to the rover.

Surface Scenarios and Mission Return

A surface mission is, by nature, a non-deterministic activity. In other words, the detailed activities of the rover on the surface of Mars cannot be planned far in advance. However, surface scenarios can be constructed by making certain assumptions about the surface environment at the landing site and using a set of standard templates for rover activities on different types of sols. The performance of these scenarios can then be measured against mission goals and objectives to see if the mission return meets expectations.

The scenarios developed to date assume that there are only seven basic "sol templates" or collections of activities grouped by the type of sol. The basic sol templates are indicated in Table 15. In the end the activities on any given sol are more likely to be a mix-and-match of various activities, than to fall into one of these specific types. They are a long-range planning convenience.

Table 15: Sol Templates

Sol Type	Sol Description
Deployment	Sols dedicated mainly to preparing for and performing rover egress.
Drive	Sols dedicated mainly to driving distances over 20 meters.
Panorama	Sols dedicated mainly to acquiring and returning wide field of view imaging or Mini-TES data for target detection and selection.
Approach	Sols dedicated mainly to getting closer to a target after it has been selected from panorama data; typically less than 20 meters of driving.
Communications	Sols spent mainly communicating data which was unable to be returned on the sol when it was acquired.
No Communications	Sols which are presumed to have no DSN coverage. These have a lot of spare energy and time for "additional mission return."
Target Science	Sols in which science experiments are actually conducted on targets which have been successfully approached to within reach of the IDD.

Surface operations are then group by sol and combined into a 91 sol surface scenario. Power draw, thermal dissipation, activity energy and time requirements, heating needs by sol and landing site, etc. are all considered in constructing surface scenarios. In addition, in order add some conservatism for operations, each scenario assumed that the objectives of one out of every three sols would be lost with no activities accomplished and no data returned.

As an example, Table 16 illustrates a surface scenario developed for a MER-A landing at the Gusev Crater site. This particular scenario represents a case with the hottest conditions at landing and the coldest conditions around Sol 90. Figure 15 shows the energy usage for this particular mission.

Table 16: Surface Scenario - MER-A Gusev Example [Tau = 0.5]

| | Sol 1-10 | | | | | | | | | Sol 11-20 | | | | | | | | | | Sol 21-30 | | | | | | | | | | Sol 31-40 | | | | | | | | | | Sol 41-50 | | | | | | | | | | Sol 51-60 | | | | | | | | | | Sol 61-70 | | | | | | | | | | Sol 71-80 | | | | | | | | | | Sol 81-90 | | | | | | | | | |
|---|---|---

Table 17 summarizes the results of three different example scenarios including the Gusev scenario described above. The table shows the surface mission duration (these cases were only run through 90 sols), the distance covered, the number of targets analyzed, the amount of data returned, and the energy spent for each mission variant.

For each scenario, the table subdivides the data return and energy usage results into three separate columns. The first data return column reports the total number of bits returned to Earth that can be used to help meet the project's mission success requirements (i.e. data above and beyond the engineering bits needed for assessing the state of the rover). The second column indicates the number of bits actually acquired in the scenario for activities directly relating to mission success. The third column is the data return margin or the difference between the first two columns. It indicates the number of bits that can be used for "additional science" activities over and above the bits required for mission success. The three energy columns are similar, but unlike the data return columns, the sum of the energy used to meet the mission success requirements (column 2) and the margin available for additional science (column 3) does not equal the available energy (column 1) as energy must be expended on the margin sols with no science benefit.

Table 17: Surface Mission Scenario Results - Mission Return and Mission Return Margins

Scenario	Sols	Meters Traveled	Locations Visited	Color Pans	Targets Analyzed	Data (Gbits)			Energy (kWhrs)		
						Number of Bits Returned Available for Mission Success	Number of Bits Acquired to meet Mission Success	Margin Above Bits Required for Mission Success	Energy Available for Mission Success	Energy Used for Mission Sucess	Margin Above Energy Required for Mission Success
MER-A, Gusev, Tau=0.5	3–90	595	4	2	6	4.7	1.4	3.3	57.2	45.6	7.3
MER-B, Isidis, Tau=0.5	3–90	510	4	2	6	4.4	1.5	2.9	55.5	49.6	3.2
MER-B, Isidis, Tau=1.0	3–90	323	2	2	4	4.1	1.2	2.9	48.2	42.5	3.5

[Assumes a 34-string solar array]

Recent Developments

The mission design for the Mars Exploration Rover mission is constantly being refined as the capabilities and limitations of the flight system and payload are better understood. As a result, the mission design baseline presented in this paper simply represents a snapshot in time and does not reflect the current state of the design in all areas. The next couple of paragraphs will briefly outline some of the changes that have recently been incorporated and a few that are likely to be introduced in the near future.

Launch Period Changes

After analyzing the launch probability of 107 Delta launches between 1989 and 2001, it was determined that the duration of the MER-A and MER-B launch periods should be increased from 18 days to at least 20 days in order to have a 99% probability of launching within each launch period. As a result, two additional launch days (and possibly three, if sufficient launch vehicle performance exists) will be added to the ends of the current MER-A and MER-B launch periods.

Flight System Changes

As a result of a number of recent changes in the flight system (principally in the cruise stage propulsion system and the entry system), a number of the masses indicated in Table 6 have increased. The current allocation for the launch mass has grown to 1072 kg.

Cruise Changes

In order to reduce the spacecraft propellant requirements, the first trajectory correction maneuver (TCM-1) has been moved from Launch + 15 days to Launch + 10 days.

EDL Changes

Due to heightened concerns regarding the impact of high, sustained horizontal winds at landing, a camera system is being developed to image the surface of Mars during the terminal descent phase of EDL. Two or three images from the camera (referred to as DIMES for Descent Image Motion Estimation Subsystem) taken a couple seconds apart would be used to direct the firing of the TIRS motors in an attempt to compensate for and reduce the horizontal velocity of the airbag system at landing.

Post-Landing Through Egress Changes

Ongoing development of the Post-Landing Through Egress phase suggests that the egress timeline reflected in this paper may be too optimistic or aggressive. Current analysis implies that egress from the lander will probably not occur until Sol 5.

Mission History / Status

Following the loss of the Mars 98 missions, NASA began a study to re-evaluate the "architecture" of the Mars exploration program. One of the first items on the agenda was to determine what type of mission should fly to Mars in the 2003 opportunity (if any, given that it was already early 2000). In the spring of 2000, a 60-day study was begun to select between a Mars Pathfinder derivative lander/rover mission and an MGS/MCO (Mars Global Surveyor / Mars Climate Orbiter) type science orbiter. Since the trajectory characteristics of the 2003 opportunity favored a lander mission, the Pathfinder derivative mission was selected.

The Mars Exploration Rover mission started out as a single rover mission, but quickly developed into a dual rover mission as the added science value of exploring two different sites on Mars and the overall mission robustness were weighed against the additional cost of building, launching, and operating two spacecraft. In August of 2000, with just under three years to launch, NASA gave the formal approval to the MER project to develop a dual rover mission. The short development cycle is virtually unprecedented for a major planetary mission.

The MER project is currently less than one year from launch. At this stage of the project, the flight system is currently in the process of testing flight hardware and software while the mission system is planning and executing tests to prepare for operations. In the coming year, the MER Mission Design Team will finalize the concepts and strategies described in this paper.

The MER mission, while similar in appearance to the Mars Pathfinder mission, represents a major advancement in capability in nearly every category as compared to the Mars Pathfinder mission. First, it is a full-fledged science mission with a payload filled with new, capable instruments. The improved navigation delivery accuracy will be able to place those instruments in previously inaccessible regions on Mars and the MER mobility system will carry them approximately 10 times farther than the Sojourner rover traveled on Mars. The adventure is about to begin.

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- EDL Analysis: Phil Knocke, Bill Strauss, Prasun Desai
- Mission Planning: Ken Fujii
- Surface Scenario Development: Bill Dias

The small images that are included at the start of mission phase sections were taken from a MER animation created by Dan Maas and Steve Squyres, the Principal Investigator for the MER project.

References

1. B. Raofi, R. S. Bhat, L. A. D'Amario, "Flight Path Control Strategies for the 2003 Mars Exploration Rover (MER) Mission," Paper AIAA 2002-4824, AIAA/AAS Astrodynamics Specialist Conference, Monterey, California, 5-8 August 2002.
2. B. M. Portock, R. J. Haw, L. A. D'Amario, "2003 Mars Exploration Rover Orbit Determination Using ΔVLBI Data," Paper AIAA 2002-4814, AIAA/AAS Astrodynamics Specialist Conference, Monterey, California, 5-8 August 2002.