MARS EXPLORATION ROVER: SURFACE OPERATIONS

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Abstract

The Mars Exploration Rover Project is an ambitious mission to land two highly capable rovers on Mars and concurrently explore the Martian surface for three months each. Launching in 2003, surface operations will commence on January 4, 2004 with the first landing, followed by the second landing on January 25. The prime mission for the second rover will end on April 27, 2004. The science objectives of exploring multiple locations within each of two widely separated and scientifically distinct landing sites will be accomplished along with the demonstration of key surface exploration technologies for future missions. This paper will provide an overview of the planned mission, and also focus on the different operations challenges inherent in operating these two very offroad vehicles, and the solutions adopted to enable the best utilization of their capabilities for high science return and responsiveness to scientific discovery.

1. Introduction

In January of 2004, Mankind will again send its robotic emmissaries to the surface of Mars. The Mars Exploration Rover (MER) mission is the United States, NASA, and the Jet Propulsion Laboratory's (JPL) response to the gauntlet thrown down by the twin failures of the Mars '98 missions. It will place two solar powered, 6-wheeled rovers onto the surface of Mars to explore two sites never before seen.

Sending new science data both directly to Earth, and using two already present JPL Mars orbiters (Mars Global Surveyor and Mars Odyssey) as orbiting relay stations, each Mars Exploration Rover will survey its landing site and select the most scientifically intriguing rocks and soil samples for in-situ investigation. It will use its unique ability to seek out and investigate rocks and soil deposits

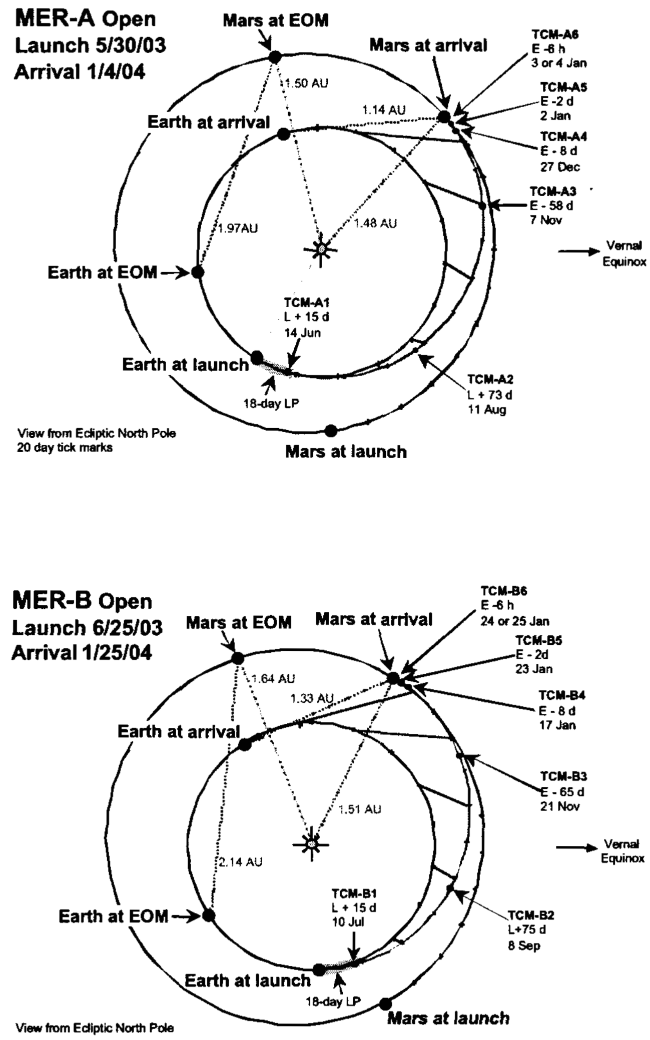

Figure 1. MER Interplanetary Trajectory

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chosen by scientists to best answer the questions posed by Mars.

Led by Project Manager Peter Theisinger from JPL and Athena Science Payload Principal Investigator Dr. Steven Squyres from Cornell University, the twin rovers will launch during the period from May 30, 2003 and July 12, 2003. As shown in Figure 1, the two spacecraft will spend a serene seven months in flight, then on January 4 and January 25 they will go through 5 minutes of nerve wracking entry, descent and landing. Then the airbag-covered landers (with the rovers inside) will roll to a stop at their respective landing sites and begin opening their petals. After rolling off the lander, the vehicles will begin their 90 Martian day examination of the Martian surface with their superb instrument suite. After thoroughly examining each site and selecting the best example rocks for each area, they will travel over to the selected rocks and place the in-situ instruments onto the rock, and measure their constituents. When satisfied of the results, each rover will have the freedom to explore over the next hill, to discover what's on the proverbial other side. After traveling over 600 meters and examining at least four different locations with each rover, the twins will have tripled the Martian ground locations examined by Humanity.

2. History

The Mars Exploration Rover (MER) Project began in the crucible of the Mars '98 twin failures. The Mars Climate Orbiter and the Mars Polar Lander both failed to reach their destination, throwing NASA and the Jet Propulsion Laboratory into turmoil. The then current plan to send both an orbiter and a lander to Mars in the 2001 launch opportunity was rapidly scaled down to a single orbiter (the Mars Odyssey Project). The debate then began to center around the 2003 launch opportunity.

Two competing concepts began to evolve. One was an orbital science mission and the other was a concept of placing a new rover on Mars to follow on to the wildly successful Mars Pathfinder Sojourner Rover. In July of 2000, MER held its Preliminary Mission Systems Design & Cost Review, fleshing out most of the major design issues and trade spaces for the development of the vehicles and their subsequent operations. Both the MER concept and the competing orbiter concept were developed and competed against one another until late July, 2000 when NASA announced the selection of the then named Mars Geological Rover, including a possible option of sending two during the 2003 opportunity. A Dual Rover Feasibility Review was held in August 2000, with a subsequent decision to approve the construction and operations of two rovers. The stage was now set for the Mars Exploration Rover to begin.

The concept selected was to use the existing Mars Pathfinder design for the entry, descent and landing of the rover. The key innovation was to deviate from the Pathfinder lander "base station" and rover approach, and to combine the base station and rover into an oversized rover. This new rover would have the basic science payload selected for the Athena payload on the 2001 rover, but be delivered by the same robust airbag delivery system used for the Mars Pathfinder[1].

This was followed by the Critical Design Review in August 2001, and a separate Mission System Critical Design Review in December 2001. These latter two reviews completed the design phase of the Project. Early March of 2002 brought the beginning of the Assembly, Test, and Launch Operations phase, with the first hardware units showing up for integration.

3. Mission Description

3.1 Mission Overview

The MER mission is divided into four separate phases: Launch; Cruise and Approach; the lander; and the Surface Mission.

3.2 Launch

The two missions, currently named MER-A and MER-B, are launched separately on Boeing Delta II launch vehicles, both from the Cape

Canaveral Air Force Station in Florida. MER-A launches on a Delta II 7925 within an 18-day launch period from May 30,2003 through June 16, 2003. MER-B launches on a Delta II 7925H "Heavy" also within an 18-day launch period, from June 25, 2003 through July 12, 2003. MER-A launches to an injection specific energy, or C_3 of 8.8 to 9.3 km^2/s^2. The later MER-B launch requires the heavy version of the Delta II due to its more demanding C_3 of 10.3 to 16.4 km^2/s^2.

The launch vehicles utilize a spinning solid upper stage for interplanetary injection. The spacecraft are separated with that spin, providing a safe and stable attitude for power and communications for several days after injection.

3.3 Cruise and Approach

MER-A and MER-B both take approximately seven months to get from Earth to Mars[2]. Spacecraft attitude is adjusted through this transit to maintain adequate power from the Sun and communications with the Earth. In addition, solar array segments are switched in as the spacecraft move further from the Sun, and antenna configurations are switched as the spacecraft move further from the Earth.

Each spacecraft's trajectory is corrected with a series of five to six translational propulsive maneuvers. The first maneuver corrects both for small errors in the launch vehicle injection and for a deliberate initial bias away from Mars for planetary protection. The remaining maneuvers adjust for improved knowledge of the trajectory through radiometric tracking and to correct errors in previous maneuvers as well as other tiny disturbances to the trajectories. The last 45 days before entry is the Approach phase. The two to three maneuvers in this phase, the last of which may be as late as six hours before entry, combined with intensive radio tracking during this phase provide for exquisitely accurate targeting of the vehicles to their designated landing sites.

NASA's Deep Space Network of 70 meter and 34 meter antennas and precision radio equipment will track the MER spacecraft and communicate with them. In addition to the standard Doppler and ranging radiometric tracking, a high-precision interferometric tracking technique using extra-galactic quasar radio sources and widely separated antennas on Earth will be relied on for the first time by MER for its approach navigation. This technique has been successfully demonstrated with the Galileo, Mars Global Surveyor, and Mars Odyssey missions.

During the Cruise phase, various checkout, characterization, and maintenance activities will be performed, including the checkout of equipment to be used in later phases of the mission.

Three hours before entry there is a final update of the entry, descent, and landing software parameters based on the best trajectory solution following the final maneuver. This is the last uplink to the vehicle before entry. The spacecraft turns to the entry attitude about one hour before entry, and separates the cruise stage 15 minutes before entry. Through all of this, communications to Earth is maintained for diagnostic purposes.

3.4 Entry, Descent, and Landing Through Egress

The landing system used by Mars Exploration Rover is based on the Mars Pathfinder lander, which successfully landed on Mars on July 4, 1997. Mars Pathfinder used a robust landing system employing a set of straightforward deceleration stages and a lander surrounded by large airbags to protect it from the first surface impact and the subsequent bouncing as it eventually rolled to a stop. The airbag system has the benefit of being tolerant to common terrain features on Mars, such as rocks up to a meter in diameter. Mars Exploration Rover will use essentially the same system, with some scaled-up components for its more massive lander, and with some landing reliability enhancements described later.

Entry begins at a defined radius from the center of Mars, which is approximately 125 km above the surface. A rapid series of critical events and activities unfolds over the next six minutes culminating in the first impact with the surface. Due to the round-trip light time to Mars of

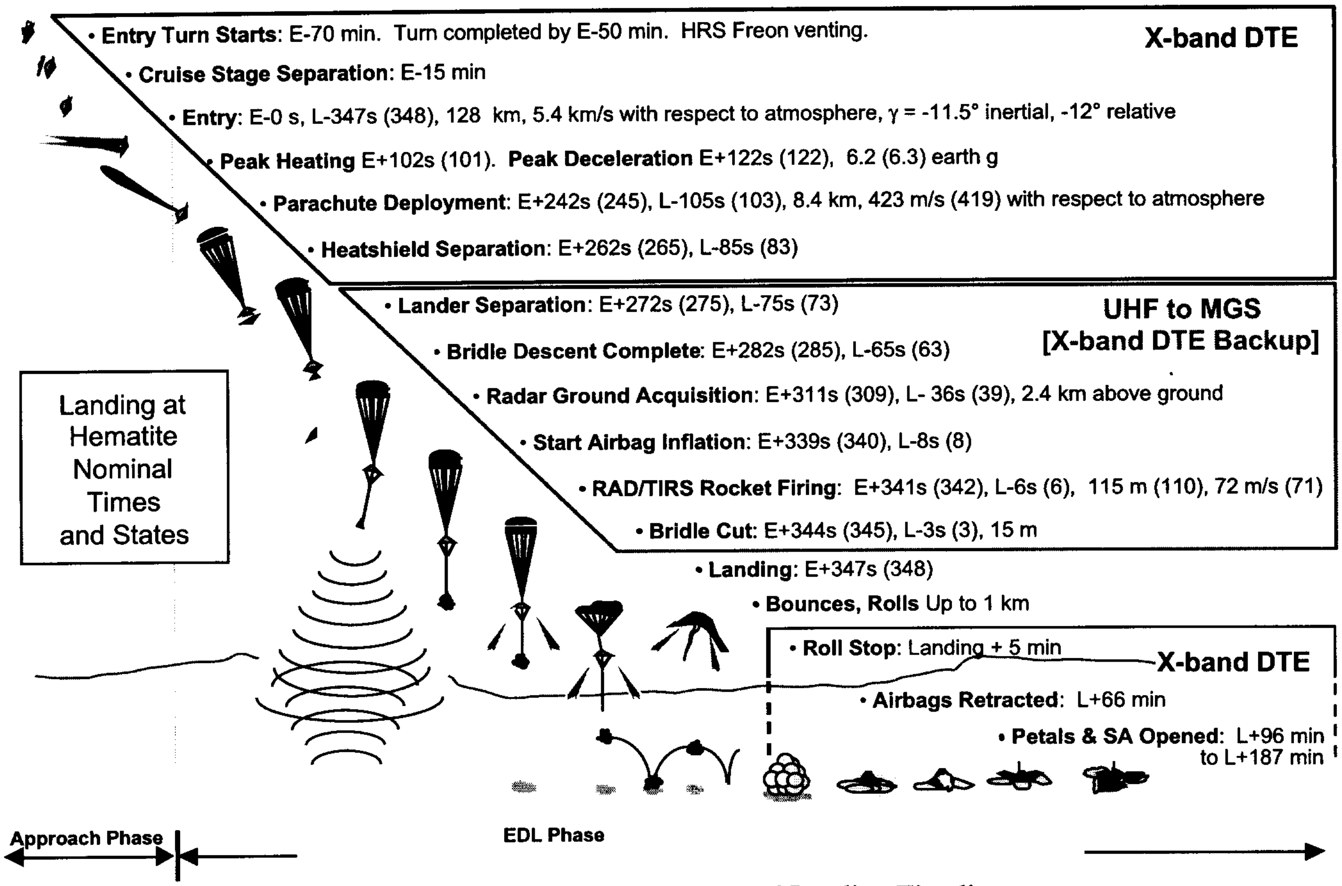

Figure 2. Entry, Descent, and Landing Timeline

approximately twenty minutes, no control from Earth is possible, so all of the events are autonomously controlled within the vehicle. Diagnostic information during this period is transmitted to Earth using an X-band link at a low rate of close to one bit per second, as well as the information that can be extracted from the Doppler shifts observed in the X-band carrier. For the final portion of the descent, diagnostic information is also transmitted to the Mars Global Surveyor (MGS) orbiter using a high-rate, eight kilobit per second UHF link. MGS is maneuvered to fly over each landing site during the entry, descent, and landing (EDL) events.

As shown in Figure 2, the vehicle enters the Martian atmosphere with a velocity of 5400 m/s. The subsequent stages of EDL are designed to reduce that velocity to zero in a controlled manner. Four minutes before impact, the entry vehicle has gone through peak heating and is at peak deceleration. Two minutes later and two minutes before impact, the heat shield has completed its job of slowing the vehicle to about 400 m/s. At that point a parachute is deployed to decelerate the vehicle further, and the bottom portion of the heat shield is separated and drops away. The lander descends on a bridle below the heat shield backshell. The parachute slows the vehicle to approximately 75 m/s over the final two minutes of descent. Eight seconds before impact, airbags are inflated that completely surround the lander in order to protect it from the first and subsequent impacts. Two seconds after airbag inflation, three solid rocket motors mounted in the backshell are fired to further slow the vehicle to close to zero velocity relative to the ground at a target altitude of 15 meters above the surface. The bridle connecting the lander to the backshell, the still-firing rockets, and to the parachute is severed to allow those articles to fly away from the lander. The lander wrapped in its protective airbags falls the last 15 meters to the first impact.

Significant atmospheric environment uncertainties and system performance uncertainties require that the vehicle evaluate its situation using several sensors in order to successfully complete EDL. Inertial measurement units are used to determine the vehicle's deceleration through the atmosphere and to decide when to deploy the parachute. A RADAR altimeter locks onto the surface about 30 seconds before impact and provides the measurements required to decide when to fire the solid motors and when to cut the bridle in order to bring the vehicle to as close as possible zero velocity at 15 meters above the surface. Due to the uncertainties, the actual altitude and velocity at bridle cut will vary from that, resulting in impact velocities on the order of 10 to 20 m/s. A system new to MER and not present on Mars Pathfinder is a set of three smaller solid rockets in the backshell that are employed under some environmental conditions to control the backshell attitude during the main solid rocket firing. This is used to avoid or cancel a horizontal velocity of the first impact that would have been induced by winds. This system makes use of both the inertial sensors to determine the backshell attitude, and a descent imager to estimate the horizontal velocity relative to the surface.

After the first impact, the lander will bounce several times and finally roll to a stop as the energy of the first impact is dissipated and the airbags begin to deflate. This may take as long as a few minutes and could cover a kilometer of distance before coming to rest. Throughout these events, the X-band transmission continues, and may be received by Earth so long as Earth is in view. The airbags are retracted, releasing any remaining gas in the bags. The retraction is completed about one hour after landing. The lander petals are then opened exposing the folded rover inside, which takes about half an hour. Shortly after that, the solar panels are deployed and the rover switches to the secondary batteries, assuring that the vehicle is power and thermally safe to survive the night and establish communications on the following morning.

The first few Martian days, or Sols, of the mission are conducted with the rover on the lander in preparation for egress of the rover off of the lander. During this time the rover makes its last use of the lander to stand up the rover into its mobile configuration and possibly to adjust the deployed lander petals to aid egress. The rover can then, by command from Earth, cut its umbilical to the lander to complete the emergence from its cocoon. Before egress, the rover takes a large number of images to provide the operators with the information they need to assess the situation and decide how to move on the lander and which way to egress, as well as to provide scientific information on the landing site to decide which way the rover will head once it is off of the lander.

<u>3.5 Surface Mission</u>

The rover is now free to investigate the landing site for the next three months. It will rove potentially hundreds of meters from the lander during its mission. The rover will perform remote sensing science with its panoramic imager and thermal emission spectrometer to provide information on the geological context of the landing site and information on nearby rock and soil targets deserving closer inspection. The rover will then drive close enough to the chosen target to be able to reach it with a robotic arm that holds in situ instruments. The arm will carefully place those instruments on the target to obtain microscopic images, and Moessbauer and Alpha Particle X-Ray spectra. An abrasion tool on the arm will cut into some of the rock targets to expose their interior and therefore their distant past to the in situ and remote sensing instruments. New targets and new locations will beckon as the rover continues to explore the landing site.

Like many of us, the rover lives its life one day at a time. Figure 3 shows a typical day in the life of a rover. Being solar powered, it will wake up in the morning around 9 a.m., may take a short siesta around noon to cool down a little, and then go to

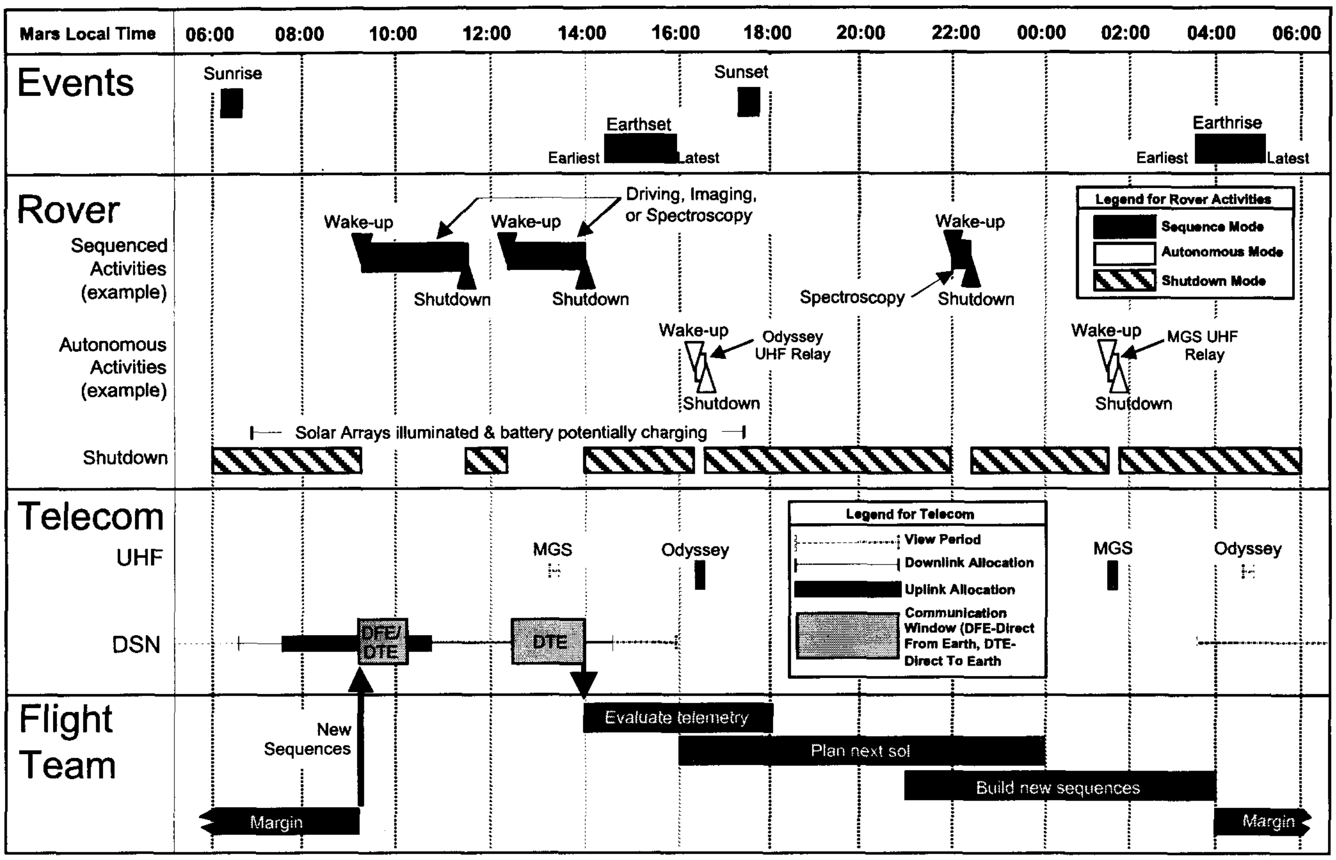

Figure 3. A typical day in the life of a Martian Rover

sleep for the night around 2 p.m. to 3 p.m to conserve energy. While asleep, the rover's computer, communications, and almost all other devices and instruments are turned off. What remains on is a part of the power system that does battery charging, performs some simple thermal control, and provides an alarm clock to wake up the computer. There is also a wakeup that is invoked when a certain amount of power becomes available from the solar panels, though normally the alarm clock will be set to wake up before that. Two of the instruments, the Moessbauer and the Alpha Particle X-Ray Spectrometers can be left on while the computer is off, in order to permit the long integration times required to get adequate signal to noise ratio. Those spectrometers have their own memory in which to accumulate data for later transfer to the computer.

The rover will also wake up for periods of several minutes at a time to relay data through the Odyssey and MGS orbiters as they fly overhead. These overflights will typically occur two to three times per day, at around 4 p.m. and 4 a.m. for Odyssey, and 1:30 a.m. for MGS (all plus or minus an hour). The afternoon MGS pass at around 1:30 p.m. will usually occur while the rover is awake. Other short nighttime wakeups may be planned to perform specialized observations, such as night-sky thermal measurements.

A typical rover day begins with a communications session directly with Earth through the rover's high-gain X-band antenna. During this session, the instructions for that day through wakeup the following day are transmitted from Earth. Contingency instructions for the following day are also transmitted, and the rover communicates back to Earth what happened overnight. The rover is then on its own to perform the requested activities. Before going to sleep, the rover will communicate directly to Earth again for one to two hours, this time with the primary objective of conveying how the requested activities went, the state of the rover, and the images and other data required by the anxious scientists and engineers back on Earth to plan the next day's activities. Normally there would be no commanding of the rover during this session.

Approximately half of the total data volume from each surface mission will come via direct communication with Earth. The other half will be through the short orbiter passes at high data rates. The orbiters will later relay those data directly to Earth. Data that are critical for next-day planning will be communicated directly to Earth during the afternoon pass. The orbiter passes will typically contain large amounts of image data for later science and engineering analyses that are not needed immediately for planning. It is possible to command the rovers through the Odyssey orbiter, though that capability will not be used in normal operations. The Odyssey orbiter will also provide Doppler-shift information from its passes over each rover that will be used to determine locations of the rovers on the surface to an accuracy of tens of meters. This will be used to locate the rovers in high-resolution orbiter imagery to better direct the rovers to areas of scientific interest.

Most of the activities that the rovers will be instructed to do fall into four generic categories: panorama, drive, approach, and target science. Each of these will typically occupy one day, in order to allow decisions on Earth to assess the activities for planning the next day. Panorama activities acquire remote sensing data about the morphology and mineralogy of the terrain visible from the rover's vantage. This information is interpreted on Earth to decide where we want the rover to go. It may take one or more days to acquire and transmit the panoramas. With that information, possibly combined with orbital data, a decision is made about where to go next, either with a long drive or a shorter approach. Drive days are for long traverses of 10 to 40 meters or more. The rover will achieve the requested driving goals with varying success and accuracy depending on the terrain encountered along the way. So again, information from this day needs to be interpreted back on Earth to decide how to proceed. Another drive day may be needed. Otherwise, the rover can proceed to an approach day. An approach day is for a short traverse, less than 10 meters, to a specific target such as a rock. A short traverse is used when high accuracy is required to bring the target within comfortable reach of the instrument arm. (Golfers might think of this as a "putt" day.) Where the rover ends up relative to the target must be assessed precisely before attempting to place the instruments on the target with the arm. The operations team on Earth will make that assessment and will either command another approach day, or if appropriately positioned will generate the exact arm motions for the next day. That day is a target science day, in which the arm places the instruments as desired on the target, possibly including an abrasion of a rock target. This may be followed by more target science days, approach days to another nearby target, or drive days to go to a more distant target or a new location. For new locations, a new panorama would be acquired to establish the context and target opportunities.

The time scales for assessing the results of a previous day and generating commands for the next, the uncertainties in the outcomes of commanded activities, and the limited resources available for energy and communication drive the surface operations design of MER.

4. Spacecraft Description

The Mars Exploration Rover (MER) spacecraft is based on the Mars Pathfinder (MPF) Cruise and Entry Descent & Landing (EDL) systems delivering a large rover (185kg versus the 11kg Pathfinder Sojourner rover) to the surface of Mars. The spacecraft design can be thought of as a "Russian doll", as it goes through several different configurations and sheds several layers before the roving mission"begins on the surface of Mars.

An exploded view of the spacecraft is shown in Figure 4. The spacecraft consists of four major assemblies: 1) Cruise Stage (~240kg), 2) Aeroshell (heat shield and back shell, ~290kg), 3) Lander

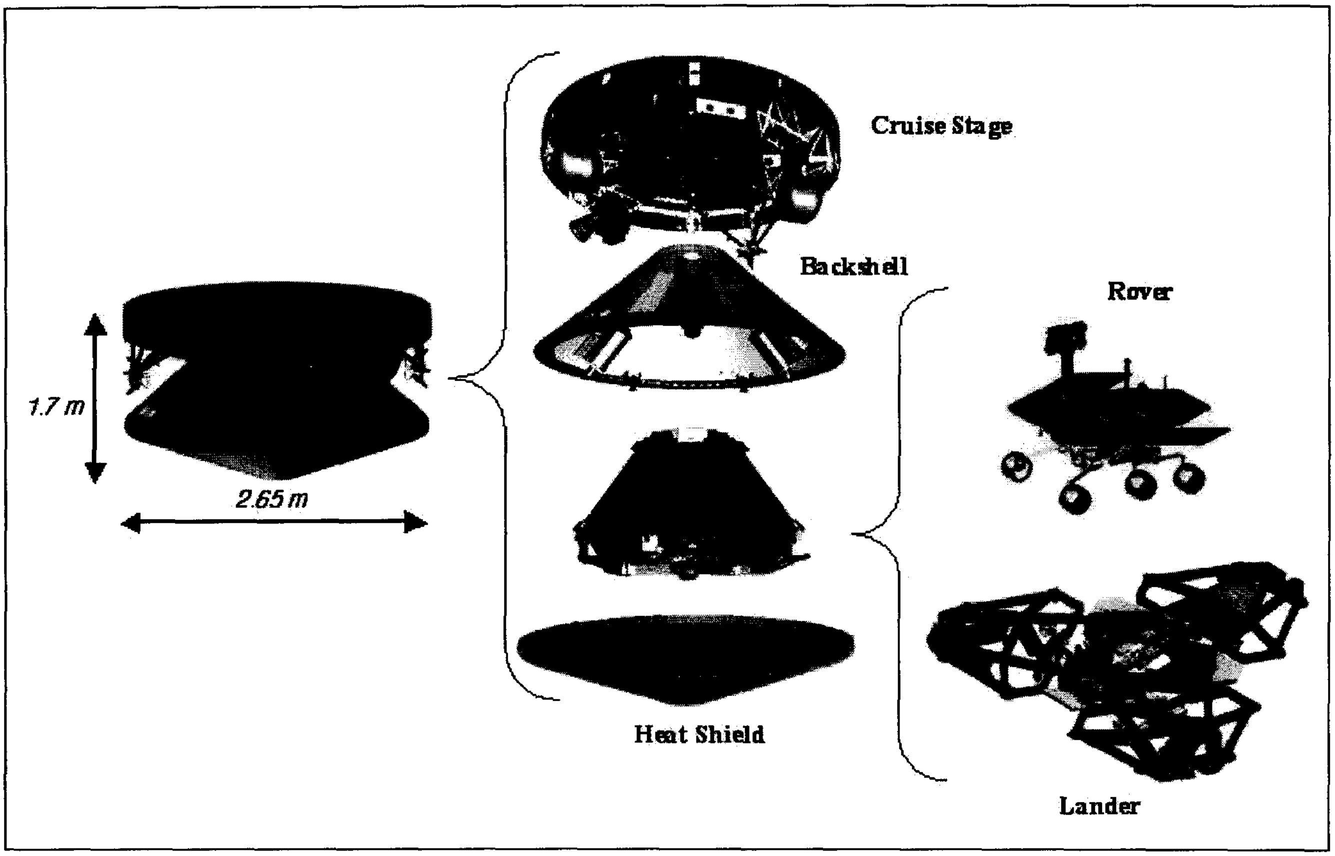

Figure 4. MER Spacecraft - Exploded view

(~350kg), and 4) Rover (~185kg). These elements are detailed in the following sections.

4.1 Cruise Stage

The configuration of the cruise stage is show in Figure 5, with details of the various components in Table 1. The cruise stage design is inherited from MPF and has overall diameter of ~2.65 meters. The inner cylindrical core forms the launch vehicle adapter and attachment point for the Aeroshell assembly. The outer ring of cruise stage is covered by solar panels to provide power during the cruise phase of the mission. The solar panels are broken into 4 segments that can be put on line as needed as the spacecraft moves further from the Sun on its journey to Mars to provide ~300W of power. The cruise stage electronics module (CEM) provides control of the propulsion system as well as analog symmetrically on the cruise stage and isolated by a latch valves. Centrifugal force produced by spinning places the propellant over the tank outlets, which are located at the outboard radial extremes of each tank.

The cruise stage has a low gain and medium gain antenna for communication during interplanetary cruise connected to X-band telecom hardware in the Rover. As the spacecraft is spin stabilized with fixed solar arrays and antennas, the attitude of the vehicle is adjusted during cruise to

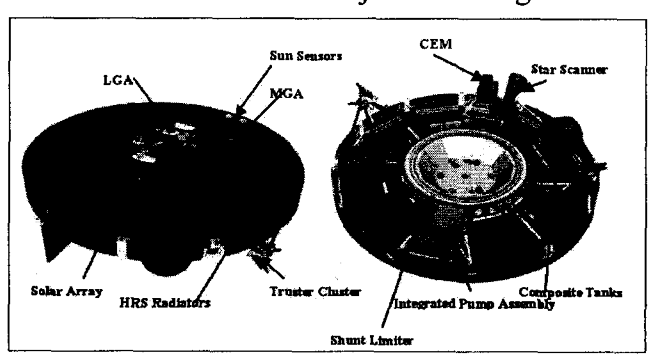

Figure 5. MER Cruise Stage

Table 1. Cruise Stage Components

Component	Prime Contractor	Description
Digital Sun Sensor	Adcole Corp	Cruise sensor for attitude determination
Star Scanner	JPL	Cruise sensor for attitude determination - Residual hardware from the Magellan Project
Solar array	Spectrolab	Triple junction GaInP 2 /GaAs/Ge cells in eight array sections
Propellant Tanks	Pressure System Inc.	Titanium hydrazine propellant tanks
Thrusters	General Dynamics	Two thruster clusters each with four 1 lbf thrusters
Integrated Pump Assembly	Pacific Design Technologies, Inc.	Redundant freon pump assembly for active heat rejection
Cruise stage structure	JPL/Composite Optics Inc.	Aluminum with composite solar array substrates
Cruse Stage electronics	JPL/Ball Aerospace	Cruise stage remote engineering unit, power conversion, power distribution, and interface electronics
Cruise stage shunt limiter unit	Ball Aerospace	Power electronics for cruise phase solar power bus regulation

best compromise between Sun pointing for solar power and Earth pointing for telecommunication.

4.2 Entry, Descent & Landing System

Each MER spacecraft will turn to its entry attitude approximately 70 minutes prior to entry into the Martian atmosphere. Five Li-SO_2 primary batteries (mounted on the lander) provide power during the EDL process and until the rover solar panels are deployed several hours later. Components of the EDL system are detailed in Table 2. Three pyrotechnic separation nuts and two pyrotechnic cable cutters are used to sever the electrical connects and mechanically separate the cruise stage from the Aeroshell approximately 15 minutes prior to atmospheric entry.

Table 2. Entry, Descent, and Landing Components

Component	Prime Contractor	Description
Aeroshell	Lockheed Martin	Composite and thermal protection Mars entry vehicle consisting of back shell and heat shield
Parachute	Pioneer	Disk-gap-band parachute for Mars atmospheric deceleration - Viking and Pathfinder project heritage design
Solid rockets	Alliant Missile Products	3 large rockets for rocket assisted deceleration (RAD) system, and 3 small traverse impulse rocket system (TIRS)
IMU	Litton	Inertial measurement unit for propagation of attitude during descent
Primary Batteries	SAFT	Non-rechargeable Li-SO2 batteries for power during Mars entry, descent and landing
Lander structure	Composite Optics	Four sided tetrahedron structure of composite and titanium enclosing rover
Airbags and gas generators	ILC Dover	Vectran airbag system encapsulating and protecting system during Mars landing
Lander petal actuators	*Aeroflex*	*Brush-less motor system for righting and opening lander*
Radar Altimeter	Honeywell	Radar altimeter for determination altitude and vertical velocity during terminal descent
Lander Electronics	JPL/Ball Aerospace	Lander remote engineering unit, power conversion, power distribution, pyro control and interface electronics

The Aeroshell, shown in Figure 6, is based on the MPF design utilizing a Viking heritage heat shield and thermal protection system (TPS). Stowed at the top of the Backshell is an MPF/Viking heritage band-gap design parachute approximately 15 min diameter, that is deployed ~10km above the Martian surface. Also mounted on the Backshell are the Backshell pyro switch assembly (BPSA) with relays controlling EDL pyro, thermal batteries to power the pyrotechnic devices, and an IMU. The IMU is used to determine parachute deploy time based on deceleration in the atmosphere and to propagate spacecraft attitude during entry and descent. Three small solid rockets mounted radially around the Backshell (called TIRS) provide horizontal impulse to correct for descent system tilt and horizontal velocity and three large solid rockets (called RADs) null vertical velocity just before landing.

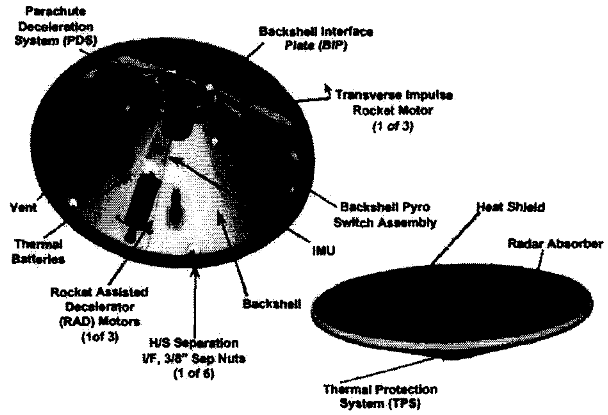

Figure 6. Aeroshell

Once the parachute is deployed, the Heatshield is released using 6 separation nuts and push off springs. The lander is then lowered from the Backshell on a ~20 meter long bridle which is stowed in one of the lander side petals. The bridle incorporates an electrical harness that allows the firing of the solid rockets from the lander/rover as well as providing data from the Backshell IMU to the flight computer in the rover.

Two sensors are used during the descent process to determine the solid rocket firing time to ensure a minimum landing velocity. A radar altimeter unit is used to determine distance to the Martian surface with first acquisition at an altitude of ~2.4 km, ~5 minutes after entry with the system traveling ~75 m/s. A nadir pointing camera is use to acquire several images of the surface that are then processed to determine horizontal velocity induced by Martian winds.

Before the solid rockets are fired, the MPF heritage airbag system is inflated to ~1.0 psig via

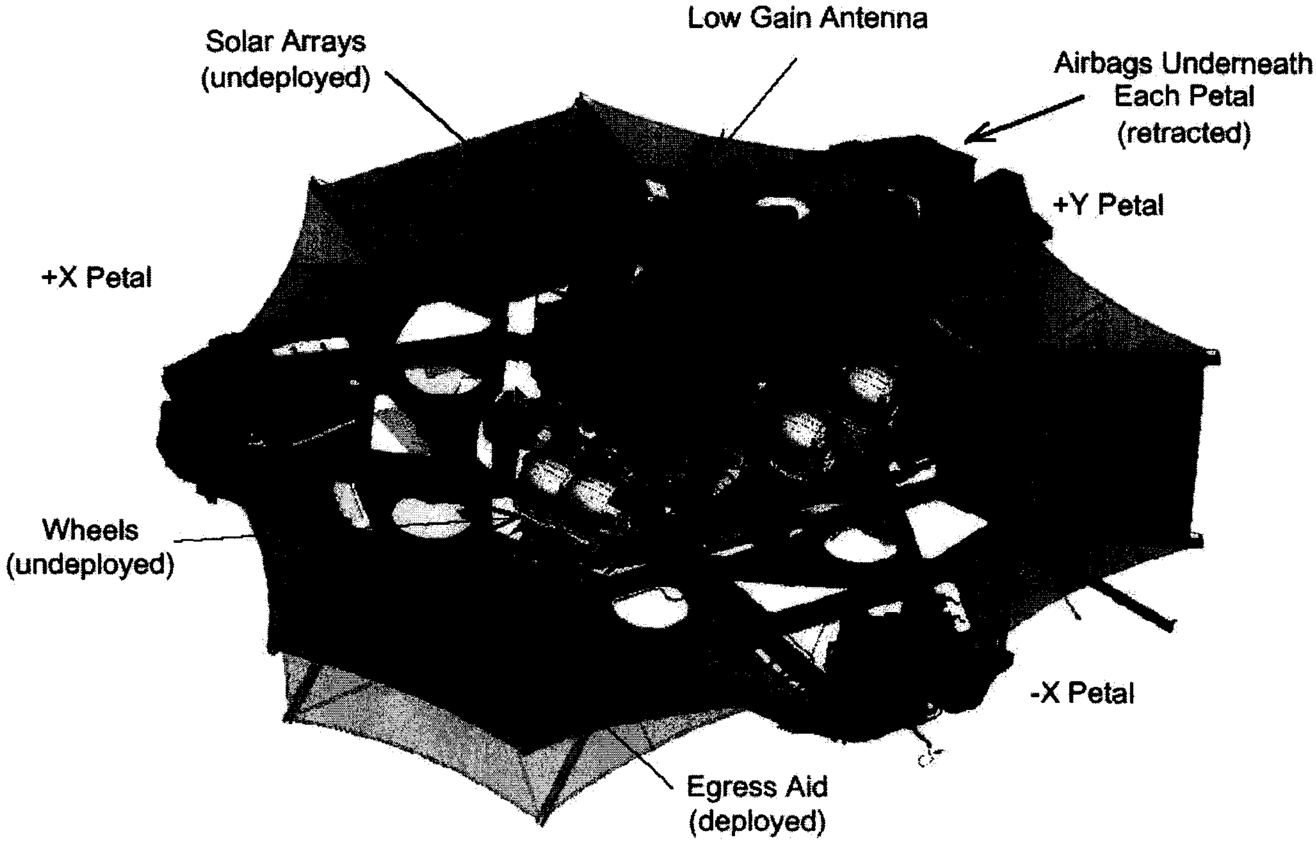

Figure 7. Deployed Lander

three pyro-initiated gas generators. The airbags consists of multiple layers of Vectran cloth and protect the lander and rover on landing. After firing the TIRS and RAD solid rockets to minimize horizontal velocity and null vertical velocity ~15m above the surface of Mars, the bridle is cut and the system freefalls to the surface, bouncing several times before coming rest on the Martian surface.

During the descent phase, the spacecraft will use a low gain x-band antenna at the top of lander tetrahedron to transmit MFSK "tones" to Earth to indicate progress. A UHF antenna also located at top of lander is used to relay telemetry to orbiting asset for later return to Earth.

Four airbag retraction actuators (ARAs) mounted under the airbags on the lander petals cause the airbags to deflate and also collect the airbag material, enabling the lander to open. The three lander petal actuators (LPAs) open the side petals and will automatically right the tetrahedron-shaped lander onto the base petal where the rover is mounted. The deployment process can take up to 2 and a half hours, depending on which petal is down when the lander stops rolling.

Figure 7 shows the lander in the deployed configuration with rover still stowed on base petal. The lander deck may sit 0.2m or more above the surface due to rocks and airbag material underneath it. Egress aids located between lander petals are passively deployed during petal opening to provide "ramplets" to aid in the rover driving off the lander onto the Martian surface. After the lander has completed its deployments, the rover will open its solar panels, deploy its high gain antenna (HGA) and Pancam Mast Assembly (PMA) and acquire the first images of the Landing site. The deployment of the rover mobility system and rover "stand up" will

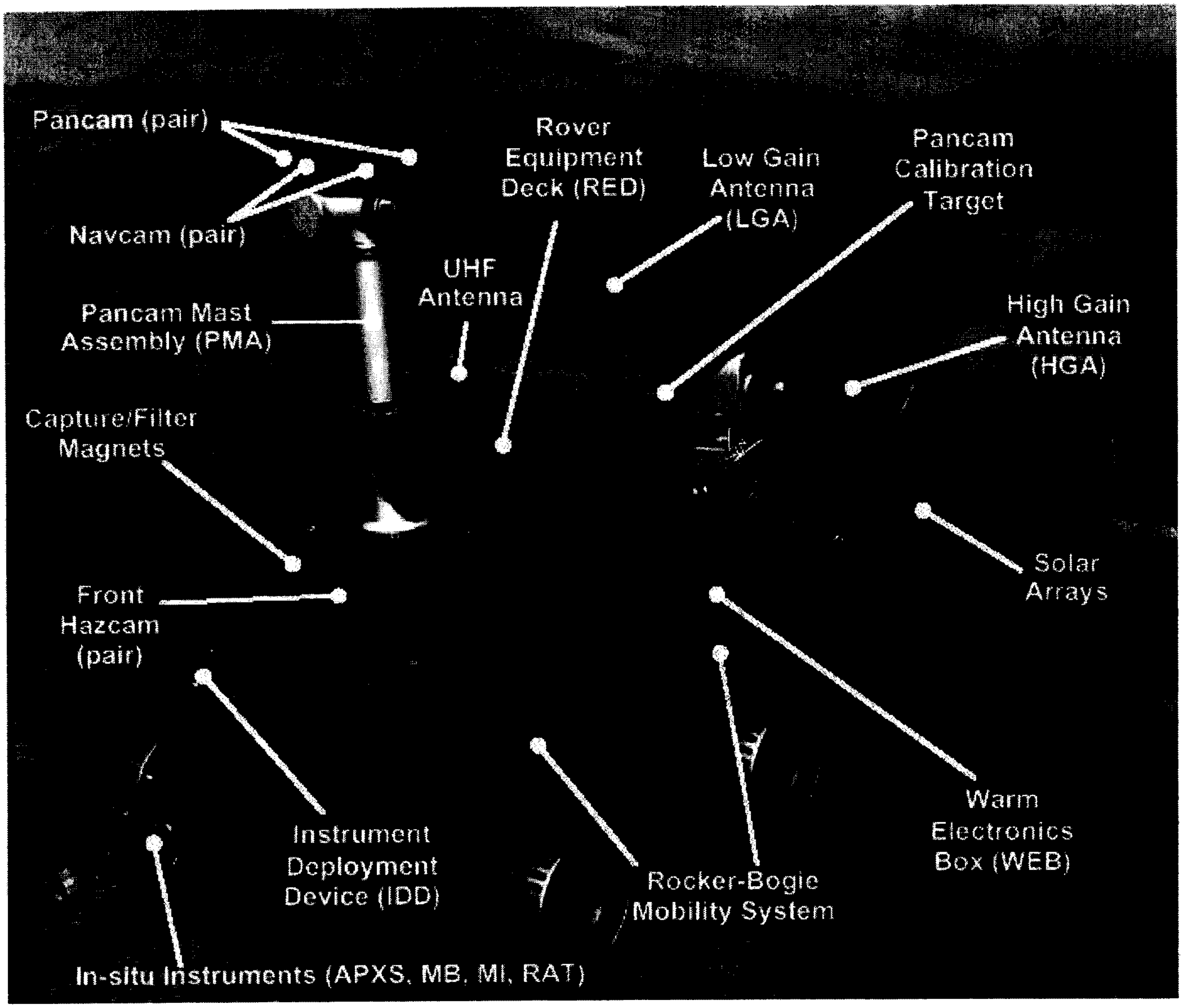

Figure 8. Rover

happen on Sol 2 once Earth has confirmed a safe landing.

4.3 Rover

The Rover, shown in Figure 8 with component details shown in Table 3, is the heart of the spacecraft and carries the main computer, telecom hardware and rechargeable batteries inside the Aerogel insulated Warm Electronics Box (WEB). The WEB and its top, the Rover Equipment Deck (RED), are comprised of Composite panels and Titanium fittings and form the primary structure of the Rover. The 6 wheel rocker-bogie mobility system is based on a scaled up version of the MPF Sojourner with 25cm diameter wheels and a footprint of ~1.4m long by ~1.2m wide. The four corner wheels are steerable, allowing the Rover to turn about its center as well as drive along arcing or straight line paths.

The Avionics in the WEB consist of a 9U VME chassis with a RAD6000 20Mhz computer, 128Mbytes of DRAM, 11Mbytes of EEPROM, and 256Mbytes of Flash storage. The avionics includes serial interfaces to science instruments and telecom

Table 3. Rover Components

Component	Prime Contractor	Description
Rover structure & mobility system	JPL	Composite/titanium rover body structure with aerogel insulation. Titanium rocker-bogie suspension with aluminum wheels driven by brushed DC motors.
Solar panel	Spectrolab	Triple junction GaInP 2 /GaAs/Ge solar cells on six deployable rover panels
Actuator gearbox assemblies	Starsys	Rover mechanism gearbox assemblies for electric motors
Brushed DC motors	Maxon	Electric motors used in rover mechanisms
Thermal Switch	Starsys	Temperature actuated thermal switch for rejection of excess rover battery RHU heat
High Gain Antenna and Gimbal	Ball Aerospace	Phased array antenna and two axis gimbal assembly for X-band communication with Earth
Pancam Mast Assembly	Ball Aerospace	Optical "periscope" for mini-TES instrument and pointable mast mount for stereo cameras
Avionics	JPL	Motor control, camera interface, flash memory, instrument interfaces, and telecom interface electronics
Flight computer	BAE Systems	20MHz Rad6000 flight computer with 128Mbytres of DRAM
Power electronics	JPL/Ball Aerospace	Rover power conversion, power distribution, shunt limiter, and battery charging electronics
Secondary Batteries	Yardney	Re-chargeable Li-Ion batteries
IMU	Litton	Inertial measurement unit for determination for rover attitude
SDST/SSPA	Motorola	Inertial measurement unit for determination for rover attitude
UHF transceiver	Cincinnati Electronics	UHF transceiver for communication relay to Earth via Mars orbital assets
Camera optics	Kaiser Electro-Optics	Optical assemblies for rover engineering and science cameras
Instrument deployment device	ASI	Robotic arm for emplacement of science instruments on rock and soil targets

hardware, a 1553 bus for communication to lander and cruise stage mounted electronics, two parallel camera interfaces that allow simultaneous stereo image capture, and closed-loop motor controllers and H-bridges for the 35 brushed DC motor on the rover and lander.

The Rover solar panel consists of five deployable sections and a fixed array on the RED with the bus voltage being controlled by a shunt regulator inside the WEB. Two Li-Ion rechargeable batteries provide 16 A-hr of energy storage for nighttime operations and peak power demands. The rover power subsystem provides over 140 power switches to control loads such as heaters and science instruments as well as pyrotechnic drivers for mechanical releases.

The Rover thermal design must maintain the equipment inside the WEB between –40C and +55C as the Mars environment goes through its diurnal cycle from approximately -95C to 0C. This is accomplished through the highly insulated WEB as well as electrical survival heaters on key components. The Li-Ion batteries have tighter temperature control limits of –20C and +30C. Radioisotope Heating units (RHUs) are mounted on the batteries to provide an additional source of heat, and wax actuated thermal switches (also mounted on the batteries) reject excess thermal energy through radiators on the sides of WEB.

The telecommunication system consists of an X-band Small Deep Space Transponder (SDST) and redundant, 15W RF output, solid-state power amplifiers (SSPA). A fixed low gain and pointable high gain antenna provide direct to Earth communications. A UHF transceiver with RED mounted monopole antenna provides an additional communication path to relay data to Earth via orbiting assets.

The Rover has two mechanisms to support science operations. The Pancam Mast Assembly (PMA) is both a pointable "periscope" for the miniature Thermal Emission Spectrometer (mini-TES) mounted inside the WEB as well as a ~1.4m high pointing system for the engineering Navcam stereo cameras and science Pancam stereo cameras. On the front of the rover is a 5-degree of freedom ~0.7 m long robotic arm for placement of in-situ science instruments on soil and rock targets of interest.

The rover sports 4 additional wide field of view engineering cameras mounted as two stereo pairs (a.k.a. Hazcams) on the front and back of the WEB, enabling autonomous hazard detection during traverse using on-board stereo processing.

4.4 Launch Vehicles

The MER spacecraft will be launched to Mars separately on two Boeing Delta II launch vehicles. MER-A is launched on Delta II 7925, and MER-B is launched on a Delta II 7925H. The basic Delta II configuration used for both of these planetary launches is a liquid oxygen and kerosene (RP-1) first stage with nine strap-on solid rocket motors, a restartable, storable liquid propellant second stage using Aerozine-50 and nitrogen tetroxide, and a solid propellant third stage. The configuration for MER-B uses larger solid-strap on motors with 25% more thrust and 40% more total impulse. This is required to reach the higher velocity required for the later MER-B departure.

The Delta II vehicles have an excellent reliability record of more than 100 launches with only two failures. They have been used on all U.S. Mars missions since 1996, beginning with the Mars Global Surveyor and Mars Pathfinder missions.

Six of the nine strap-on motors augmenting the first stage loft the vehicle for the first minute of flight. Those six motors separate and fall away and the three remaining strap-ons are ignited and augment the first stage for the second minute of flight after which the remaining three separate and fall away. The first stage continues on its own for another two minutes to reach space and 80% of orbital velocity. The spent first stage then separates and the second stage is lit, burning a portion of its propellant for four to five minutes to take the vehicle into a low Earth orbit. During that time, the fairing that protected the third stage and the MER spacecraft from the atmospheric ascent is jettisoned.

The vehicle coasts in this park orbit for 20 to 60 minutes. At the proper time to intersect the outgoing trajectory to Mars, the second stage is restarted and burns for two minutes to begin the escape from Earth's gravity. A spin table mounted on the second stage spins up the third stage solid motor and spacecraft, which then separates. The third stage ignites and burns for 90 seconds to complete the escape from Earth and to reach an accurate insertion to the desired trajectory. The third stage is spin stabilized, and has active nutation control to maintain the spin axis. After the burn is complete, a de-spin system using weights deployed on long tethers brings the spin rate down from 70 rpm to 12 rpm. The MER spacecraft is then separated spinning, ready for acquisition and commanding by the MER operations system. The trajectory is intentionally biased a small amount away from Mars, so that the spent third stage will miss the planet and avoid any potential contamination that might confound future science investigations. The MER spacecraft's first maneuver will cancel that bias and place itself on a trajectory to Mars.

5. Science Objectives and Instruments

Most of the science objectives of the Mars Exploration Rover mission are aimed at extracting geologic clues to past water activity, geologic processes, and past environmental conditions on Mars. The objectives are to:

1. Search for and characterize a diversity of rocks and soils that hold clues to past water activity (water-bearing minerals and minerals deposited by precipitation, evaporation, sedimentary cementation, or hydrothermal activity)
2. Investigate landing sites, selected on the basis of orbital remote sensing, which have a high probability of containing physical and/or chemical evidence of the action of liquid water
3. Determine the spatial distribution and composition of minerals, rocks, and soils surrounding the landing sites
4. Determine the nature of local surface geologic processes from surface morphology and chemistry
5. For iron-containing minerals, identify and quantify relative amounts of specific mineral types that contain H_20 or OH, or are indicators of formation by an aqueous process, such as iron-bearing carbonates
6. Characterize the mineral assemblages and textures of different types of rocks and soils and put them in geologic context
7. Extract clues from the geologic investigation, related to the environmental conditions when liquid water was present and assess whether those environments were conducive for life
8. Calibrate and validate orbital remote sensing data and assess the amount and scale of heterogeneity at each landing site

The last objective (8) will allow us to better understand the global and regional data sets for Mars collected by Viking, Mars Global Surveyor, and Odyssey, and to extrapolate what we learn about the geology of the two landing sites to larger regions on Mars.

To meet these objectives, landing sites will be selected at which the rover and its payload can be used to test scientific hypotheses related to past water activity. At each landing site, the rover will examine its surroundings using the remote sensing instruments, and then drive to selected rocks and soils of interest for in-situ instrument analysis and additional close-up remote-sensing characterization. Table 4 summarizes the instruments and their

Table 4. MER Science Instruments

Instrument Name	Lead Investigator	Institute	Prime Contractor	Prime Use
Panoramic Camera (Pancam)	*Dr. James F. Bell III*	*Cornell University*	*n/a (JPL built)*	*Multi-spectral stereo* remote sensing in the 400 to 1100 nm wavelength range
Miniature Thermal Emission Spectrometer (Mini-TES)	Dr. Philip Christensen	Arizona State University	Raytheon Santa Barbara Remote Sensing, CA	Infrared remote sensing in the 5 to 29 micrometer wavelength range
Rock Abrasion Tool (RAT)	Steve Gorevan		Honeybee Robotics, NY	Expose un-weathered rock for analysis by other instruments
Mossbauer Spectrometer (MB)	Dr. Goestar Klingelthoefer	Johannes Gutenberg University, Mainz, Germany		Rock and soil iron oxidation state and iron-bearing mineral identification
Alpha Particle-X-Ray Spectrometer (APXS)	Dr. Rudolf Rieder	Max Planck Institute fur Chemie, Mainz, Germany		Rock and soil elemental chemistry
Microscopic Imager (MI)	Dr. Kenneth Herkenhoff	US Geological Survey, Flagstaff	n/a (JPL built)	Close-up imaging of rock and soil at 30 micrometers per pixel
Magnet Arrays	Dr. Morten Madsen	University of *Copenhagen, Denmark*		Capturing magnetic *dust for examination* by the other instruments

On Mars, the rovers' remote sensing science instruments will view the surrounding terrain from a height 1.5 m above the ground. These two instruments are a mid-infrared point spectrometer called the Miniature Thermal Emission Spectrometer (Mini-TES) and Panoramic Camera (Pancam), a high-resolution stereo color imager. Elevation and azimuth actuators provide the ability to acquire 360-degree panorama data sets for both Mini-TES and Pancam.

Pancam has two 1024 x 1024 CCDs, each with its own filter wheel, to examine the rover's surroundings in stereo and in 14 different bandwidths over the 400 to 1100 nm wavelength range. The maximum angular resolution of Pancam, 0.28 mrad/pixel, is three times higher than that of the Mars Pathfinder camera. The Mini-TES infrared spectrometer produces high spectral resolution (10 cm^{-1}) image cubes over the wavelength range of 5-29 micrometers, with a nominal signal-to-noise ratio of 450:1, and angular resolution modes of 20 and 8 mrad. With this performance and wavelength range, Mini-TES can detect and identify fundamental absorption features of rock-forming minerals. The mineralogical information that Mini-TES and Pancam provide will be used to help select the rocks and soils for the rover to visit and investigate in more detail. In addition, Mini-TES will provide information on the thermal inertia of rocks and soils and provide upward-looking temperature profiles through the atmospheric boundary layer. Upward-looking measurements by Pancam will provide information on atmospheric dust size distribution and abundance.

After rock and soil targets have been identified from a distance using Pancam and Mini-TES, and the rover has driven to them, they will be studied in more detail using three instruments and an abrasion tool on the end of a five-degree-of-freedom robotic arm. The arm can position these instruments and tool directly on a rock or soil of interest, and position them all on the same spot. One of the instruments is an Alpha Particle-X-Ray Spectrometer (APXS), an improved version of the instrument that flew on Mars Pathfinder. Radioactive alpha sources and alpha and X-ray detector measurements will provide elemental chemistry of rocks and soils, which constrains the mineralogy and petrology. Another instrument on the arm is the Mössbauer Spectrometer (MB), which is an instrument used to identify iron-bearing minerals and determine iron oxidation state.

The MB measures the resonant absorption of gamma rays produced by a ^{57}Co source to determine splitting of nuclear energy levels in iron atoms, which is related to their surrounding electronic environment. The third instrument on the robotic arm is the Microscopic Imager (MI), which will acquire images with a spatial resolution of 30 micrometers/pixel over a 6-mm depth of field. It uses the same CCD detectors as Pancam.

Three different magnets on the rover deck and a set of magnets in the RAT will be periodically examined by Pancam and IDD instruments. This will provide constraints on the chemical and mineralogical content of the magnetic fraction of the airborne and rock-grinding dust.

In order to get around the problem of dust coatings and possible weathering rinds, the robotic arm payload also includes a Rock Abrasion Tool (RAT). After being positioned against a rock, the RAT uses mechanical grinding heads to remove an outer cylinder of rock 5 mm deep by 45 mm in diameter. The area exposed can then be investigated in detail using all of the instruments on the payload. Measurements can be made before and after using the RAT to assess the nature of a weathering rind if one is present. Comparison of the chemistry and mineralogy of an unweathered rock interior with an outer weathered surface could yield clues to a past weathering process involving water. Being able to analyze rock interiors will represent a major advance over the measurements at Pathfinder, which were heavily contaminated by dust.

The synergy of using multiple instruments on the same spots on individual rocks and soil patches, carefully chosen to characterize the diversity at each landing site, will be key to a successful science mission. This synergy is what really makes mineral identification possible. Panoramas and images from the remote sensing instruments will allow us to carefully select the samples for detailed study and to put the well-characterized samples in the broader context of the geology of the site. Relating all this to the orbital remote sensing data sets will provide even broader geologic context for each landing site, as well as two comprehensive sets of ground-truth for the orbital measurements.

6. Operations Challenges

The MER mission scenario presents several operations challenges, the combination of which are unique in the history of deep space exploratory missions. The design of the MER surface operations process is largely a response to the need to operate the two rovers in a reactive mode, in which the plan for the next set of activities depends heavily on the success in carrying out the prior sol's activities.

Several key rover surface functions are inherently non-deterministic in their duration and execution, precluding precise a priori modeling by the ground system. Rover traverse is always subject to dead reckoning error, so the rover will never end up exactly where ground operators intended it to go. Contact forces during instrument placement may cause rocks or the rover to shift. The time required to traverse a given patch of terrain varies with the number of hazards encountered, the coefficient of friction of the terrain surface, and the specific geometry of the terrain. As soon as the rover moves some distance from the vantage point of the images available to ground operators for traverse planning, the rover's knowledge of the terrain becomes superior to that of the operations team, leading to unanticipated—but correct—onboard autonomous navigation decisions, again not modeled by the ground system. The time required to grind a rock to a specific depth is a function of rock hardness, which also cannot be ascertained prior performing the operation. As a consequence of these unavoidable uncertainties, the development of a relevant command upload for tomorrow cannot begin until the results for today have been downlinked and provided to ground operators. This constraint, together with the limited duration of the surface mission, drives the operations design to turnaround command loads quickly and often.

A number of operations constraints are derived from the rover's dependency on solar arrays for energy. The rover's activities must generally be performed during daylight hours, and the rover must remain largely quiescent overnight. Thus the rover's activity cycle is slaved to the twenty-four hour thirty-nine minute Mars local time at the landing site. Another consequence of solar array dependence is that the rover is an energy-starved system. The upper limit on the lifetime of the rover is determined by the energy available to it as the mission progresses. Dust deposition on the solar arrays (Mars Pathfinder experienced 0.2 to 0.3% increase in dust accumulation per sol) is expected to reduce energy available to the rover by approximately 25% by the end of 90 sols.

The rover energy budget does not permit it to communicate continuously, and energy allocated to communications must be traded off with other rover functions. In fact, the rover must regularly shut down during parts of the Martian day to conserve energy and charge its batteries. Direct-to-Earth communication is generally restricted to one morning session during which the rover receives its commands for the sol, followed by a one to two hour afternoon downlink session during which the rover communicates critical telemetry containing the results of the sol's activities. The DTE communications is supplemented by up to four UHF orbiter relay passes by Odyssey and MGS. These relay passes are far more efficient from a rover energy standpoint, transferring as much data as a DTE session in only a few minutes, but the orbiter links are subject to significant latency, on the order of many hours to days, making them virtually useless for rapid-turnaround operations. Only non-time-critical telemetry is nominally assigned to the UHF relays.

In summary, the MER surface operations design must support:

1 Once-per-sol upload of command sequences governing all rover activities the next twenty-four or more hours

2 Every sol commanding of each rover (seven days per week)

3 Rapid command turnaround (downlink-to-uplink time of approximately 19 hours)

4 Limited communications opportunities

5 Bounded non-determinism in the execution time of selected key activities (e.g., rover traverse, RAT operations)

6 Inability onboard to unambiguously assess the success of traverse and instrument placement activities

7 Conditionality within command sequences (for sequenced anomaly response, as well as opportunistic science in the event of early completion/failure of a nominal plan)

8 Achievement of all mission objectives within the projected total surface mission lifetime of approximately 90 sols

7. Operations Plans and Strategies

7.1 Overview of Surface Operations

Surface operations processes are of two primary types: strategic and tactical. Strategic tasks are defined as those that can be carried out over multiple days and can be performed during standard work shifts. Among the MER operations strategic tasks are:

1 Mid- and long-range surface strategic plan development

2 Communications planning

3 Inter-mission coordination

4 Mission Success tracking (updates to the mission success "scorecard")

5 Science and engineering data product generation

6 Validation of new activities and sequence templates

7 Model updates

8 Re-transmission assessment and request generation for non-critical data (i.e., telemetry not necessary for immediate operations planning and decision-making)

The strategic and tactical operations processes are described in more detail in the following sections.

7.2 Tactical operations

7.2.1 "Mars Time" Staffing Schedule

Operating a solar-powered rover on the surface of Mars presents a human factors dilemma; the rover's activities are synchronized with the Mars local time of day, while Earth-bound operations personnel schedules are normally synchronized with the Earth local time of day. Since a Martian day ("sol") is about forty minutes longer than an Earth day, how would MER reconcile Mars and Earth clocks for efficient surface operations?

Surface mission staffing approaches and related human factors issues were assessed over a one-year period early in the MER project. A workshop in January 2001 brought together human factors experts to address the feasibility of a Mars-time operations schedule and recommend fatigue mitigation strategies for intense surface operations. In the summer of 2001 the Human-Centered Computing group at NASA Ames Research Center conducted a fatigue/stress survey of former participants in the Mars Pathfinder mission, the only known case of operations personnel working a Mars-time schedule for an extended period. The survey provided the first non-anecdotal summary of the Mars Pathfinder operations experience. Finally, a working group composed of MER engineers

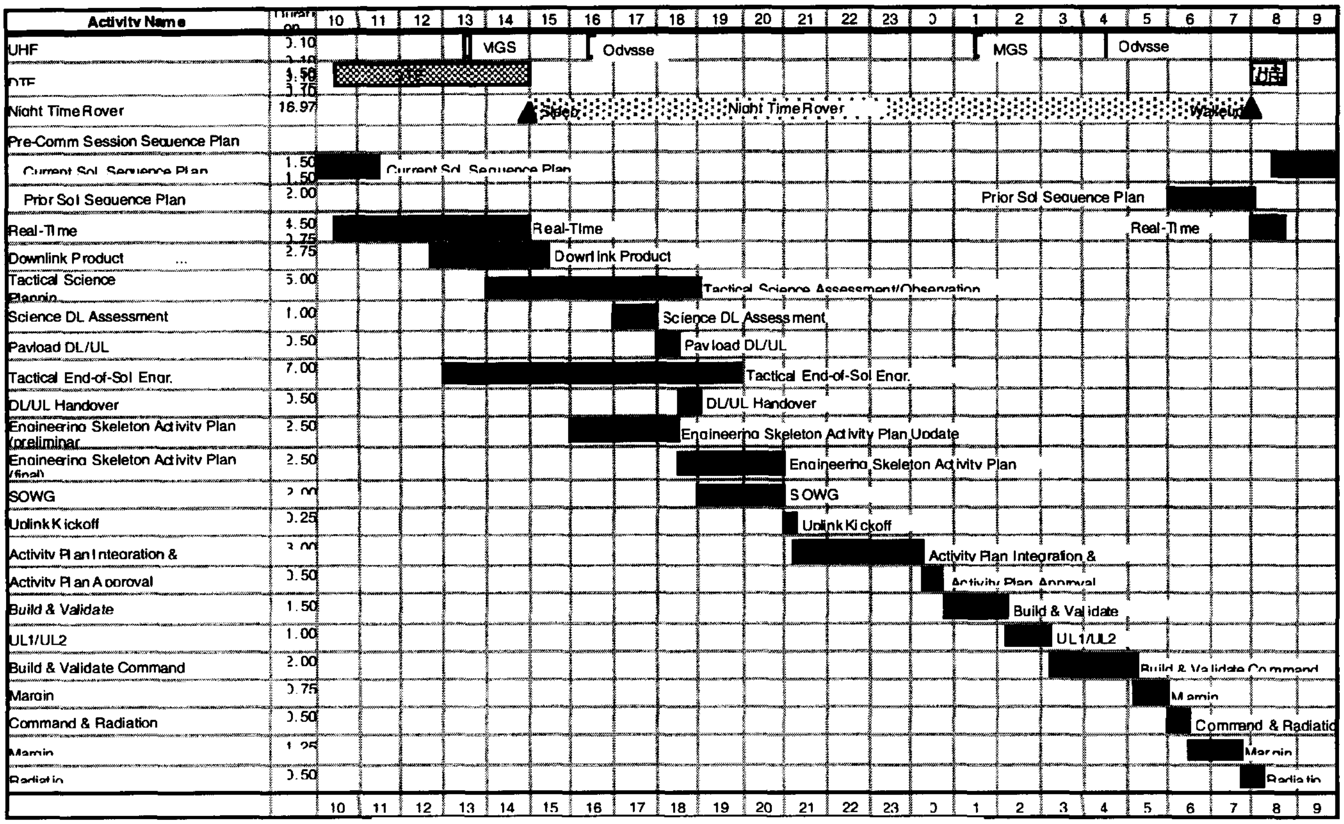

Figure 9. Tactical Operations Timeline

generated a set of metrics and proceeded to evaluate a Pathfinder-like Mars-time schedule and ten other staffing alternatives to identify an appropriate staffing policy for MER surface operations.

The results of all three activities supported the feasibility and efficiency of Mars-time staffing approaches. Mars-time schedules were more disruptive to team members' personal lives, but could be sustained without undue hardship over the limited duration (less than fours months) of the surface mission. (A surprising conclusion of the survey was that Pathfinder veterans *preferred* a Mars-time schedule, with appropriate days off, to working a standard eight-to-five "Earth Day" schedule for operating their mission.) Mars-time was consistently superior in terms of mission objectives accomplished per day of operations, reduced the probability of errors across shift hand-overs, and required fewer personnel to implement than other approaches. One of the key lessons was that the specific schedule worked was less important than ensuring that individuals got sufficient sleep, took enough days off, and did not work too many consecutive hours. The MER project concluded at the end of the Mars-time investigations that the tactical operations teams would work a 4-days-on/3-days-off rotating Mars-time schedule, with personnel work shifts starting forty minutes later each day than the day before, throughout the surface mission.

Additionally, since the MER-A and MER-B landing sites will be located at different longitudes on the planet's surface, the rovers will in effect be operating in two distinct Martian time zones. The tactical operations personnel will be split into two virtually independent teams, one living in the MER-A Martian time zone, and the other living in the MER-B time zone.

7.2.2 Tactical Overnight Timeline

The tactical operations flow follows the timeline illustrated in Figure 9. The scale for the timeline is in units of Mars local time, since operations flow for a given rover (MER-A or MER-B) will be slaved to the Mars clock associated with that rover's landing site.

At the start of the "Downlink" shift, members of the Spacecraft/Rover Engineering Team (SRET) review the sol-n uplink report, which defines the activity plan and associated command sequences governing the rover's actions for the current sol. The uplink report, together with face-to-face interactions with uplink personnel about to go off-shift, provides the SRET members with context for the upcoming sol-n afternoon Direct-to-Earth downlink from the rover. Review of the report must be completed prior to the start of the downlink.

The exact time and duration of the rover's Direct-to-Earth (DTE) downlink will be specified one or more sols in advance of a given communications session, and will depend on the pass allocation, rover activities planned for the sol, energy available, and other factors. In general, the "afternoon" DTE will continue for one to two hours and take place sometime between 1030 and 1500 Mars LST. During the DTE, the real-time operations engineer and members of the SRET team monitor "either go to rock A and do observations a, b, and c, or go to rock B and do observations x, y, and z") when the feasibility of an activity cannot be fully evaluated until later in the uplink planning process.

At the next step, the uplink team integrates the science activity plan with engineering activities, and evaluates the feasibility of proposed terrain-dependent activities (i.e., rover traverse and robotic arm motions). The SRET team delivers the final results of downlink analysis before the bulk of the team goes off-shift. Competing science alternatives are whittled down and, as necessary to stay within resource constraints, lower priority activities are deleted from the plan. The overall activity plan is iterated until a conflict-free plan is produced that can be implemented, with margin, fully within the available resources. This plan is reviewed at the Activity Plan Approval meeting (which occurs approximately nine hours after the end of "afternoon" downlink), at which time the Mission Manager approves, modifies, or rejects the plan. (A rejected plan, when it occurs, may result in no command load for the sol, leaving the rover to execute its "runout" sequence already on board.)

Assuming an approved activity plan, the uplink engineers will then begin building and validating the command sequences comprising the command load. But with only three hours remaining to the ten hour "Uplink 1" shift, they cannot expect to finish the job. Instead, one hour before then end of the shift, a fresh team on the "Uplink 2" shift arrives. Over the course of an hour, the sequence developers on the first shift hand over their partially completed products to their counterparts on the next shift. With the help of automated documentation and face-to-face interactions, the Uplink 2 shift completes the command load.

The final command package is presented to the Mission Manager at the Command and Radiation Approval meeting, which takes place about fifteen hours after the end of the afternoon downlink. The command load is then radiated to the rover during the "morning" DTE communications session, which takes place at approximately 0800 Mars LST. The second uplink shift completes the documentation of the sol-n+1 uplink report, which provides the necessary context to the incoming Downlink shift for interpretation of the rover's actions.

7.3 Strategic Operations

The MER surface mission strategic operations timeline is represented in units of days, rather than hours (see Figure 10) Whereas the MER-A and MER-B tactical teams work almost entirely independent of each other, strategic personnel work together to ensure that the accomplishment of the overall objectives of the MER mission, being fulfilled by two rovers half a planet apart, will be fully coordinated.

The Mission Planning Team (MPT), on a three-day timeline, develops two week strategic surface activity plans for both the MER-A and MER-B rovers. These strategic plans incorporate negotiated support from all communications assets, including the orbiters Odyssey and MGS, and the

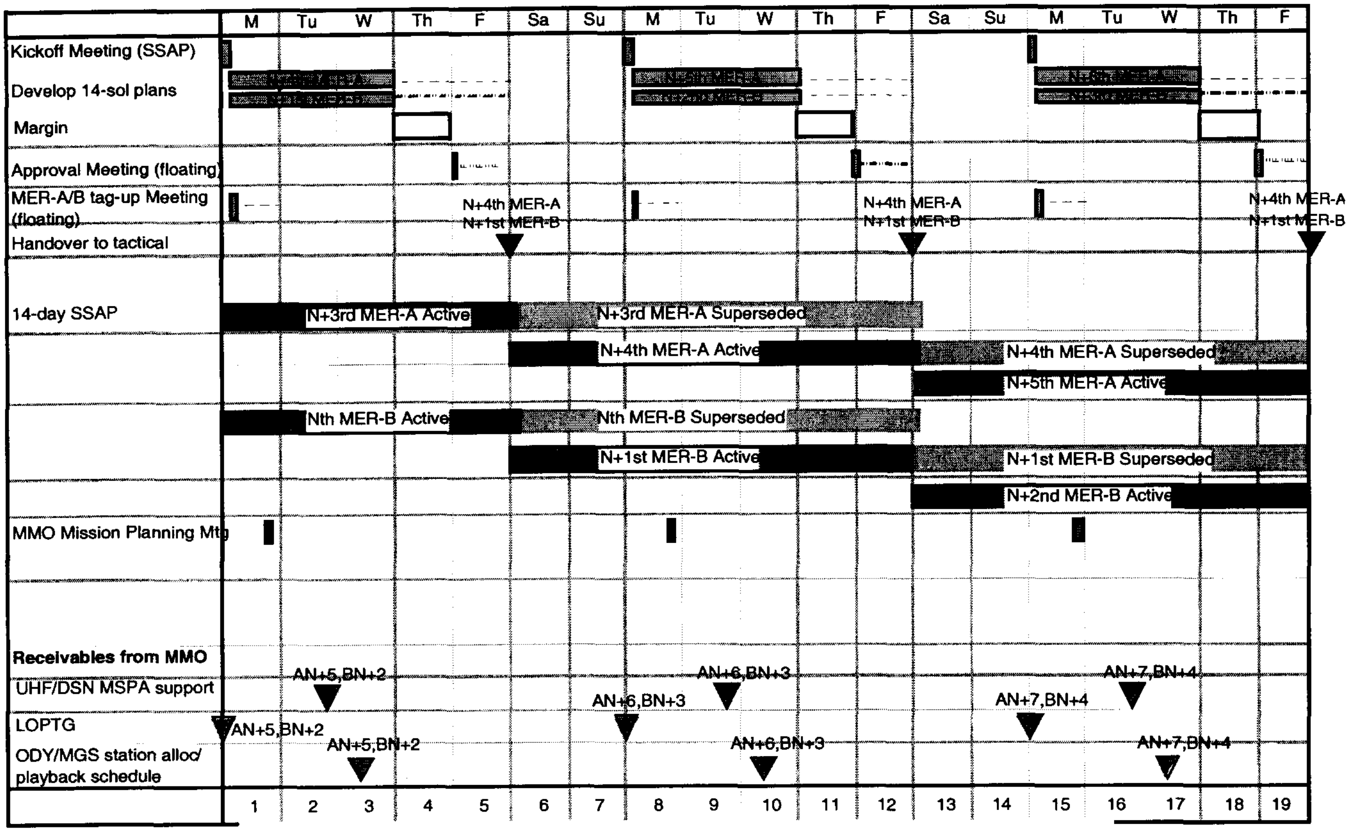

Figure 10. Strategic Operations Timeline

DSN station allocations. The Odyssey and MGS missions do not have "tactical" processes in the MER sense, and UHF relay coverage must be negotiated and modified at the strategic level. Representatives from the Long Term Science Theme groups for MER-A and MER-B, who work tactical shifts most days of the week, provide science inputs to the planning process.

Once the strategic plans are approved, Mission Planners—straddling the strategic/tactical boundary—present the strategic plans at the tactical SOWG meetings to keep the tactical activities aligned with the mission objectives. While the strategic plans look 14 sols into the future, the Mission Planning Team has no illusion that its plans will remain accurate for the full two weeks. Recognizing that the uncertainties in rover traverse and command execution will cause the reality of rover accomplishments to begin diverging from the plan almost immediately, the MPT delivers a new set of two week plans every week. By this mechanism, the MPT provides context and guidance to the tactical teams, while remaining relevant in the face of unforeseen occurrences on the tactical time scale.

The MPT also tracks the status of mission objectives (e.g., number of targets analyzed, distance traversed) across both MER-A and MER-B. As each rover completes an objective, the MPT updates the so-called mission success Scorecard, summarizing the current state of the mission vis-à-vis minimum and full mission success. The Scorecard status will influence the content of the next strategic surface activity plan, and will be presented at the tactical SOWG meetings to provide context to the tactical operations teams that otherwise would be focused only on the next sol.

The fast-turnaround tactical process depends on the availability of pre-defined activities and sequence templates to enable the development of validated command loads without requiring daily execution of all sequences on a flight testbed. While most activities and templates will themselves be defined during the MER development and cruise phases, new templates and activities may be identified and developed during surface operations. There is not time within the tactical process to perform the necessary validation of new templates or to add to entries to the activity dictionary. Responsibility for these functions is shared by SRET and IST engineers assigned to the strategic process. These engineers will write template sequences, determine the sequencing rules governing their use, and execute template sequences on the flight testbed. Once a template is fully validated, it will be delivered to the tactical teams for their use.

Another function performed at the strategic level is team management and personnel scheduling. The team chiefs for teams with tactical participation (SRET, IST, SOST, SOWG) work staffing issues across all personnel on their teams, whether currently assigned to tactical or strategic processes. This enables the team chief to reassign personnel if, for example, a particular technical expert working the MER-A tactical process must be brought over to deal with an anomaly on MER-B. In the event of a major anomaly, some strategic functions may become temporarily irrelevant, and the team chief can reallocate those personnel to work the anomaly recovery process on a tactical basis.

8. Summary

The Mars Exploration Rover mission will challenge JPL and NASA's abilities, but in return will provide a wealth of scientific knowledge. It will enable us to conduct field geology on Mars, at two distinct sites. At each site, the mission will be able to investigate different locations chosen by an expert team of scientists, and use their expertise to look for the best rocks and soil samples for investigation.

In addition, it should provide the same world class excitement for the public that was provided by its Mars Pathfinder predecessor. From January 4, 2004 until the end of April, 2004, the world's attention will be captured by this pair of capable robot explorers.

9. Acknowledgments

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