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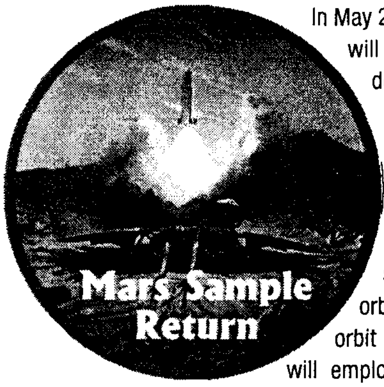
MISSION DESIGN OVERVIEW FOR MARS SAMPLE RETURN

Wayne Lee[1], Louis D'Amario[2], Ralph Roncoli[3], John Smith[4]



In May 2003, a new and exciting chapter in Mars exploration will begin with a launch that will ultimately lead to the delivery of samples from the Red Planet to Earth. This proposed Mars Sample Return (MSR) project is being conducted by NASA in conjunction with the French space agency CNES, and will utilize launches in both 2003 and 2005 with an expected sample return in October 2008. The baseline mission mode selected for the MSR mission is Mars orbit rendezvous, analogous in concept to the lunar orbit rendezvous mode used for Apollo. Specifically, MSR will employ two NASA-provided landers of nearly identical design and one French orbiter carrying a NASA payload of rendezvous sensors, orbital capture mechanisms, and Earth return capsules. The high-level concept is that the landers will launch surface samples into Mars orbit, and the orbiter will retrieve the samples in orbit and then carry them back to Earth. This paper will provide an overview of the preliminary mission design for the Mars Sample Return.

Mission Synopsis

The first MSR element to depart for Mars will be one of the two NASA-provided landers. Currently, it is proposed that an intermediate-class launch vehicle, such as the Boeing Delta 3 or Lockheed Martin Atlas 3A, will launch this 1800-kg lander from Cape Canaveral during the May 2003 opportunity. The spacecraft will utilize a Type-1 transfer trajectory with an arrival at Mars in mid-December 2003.

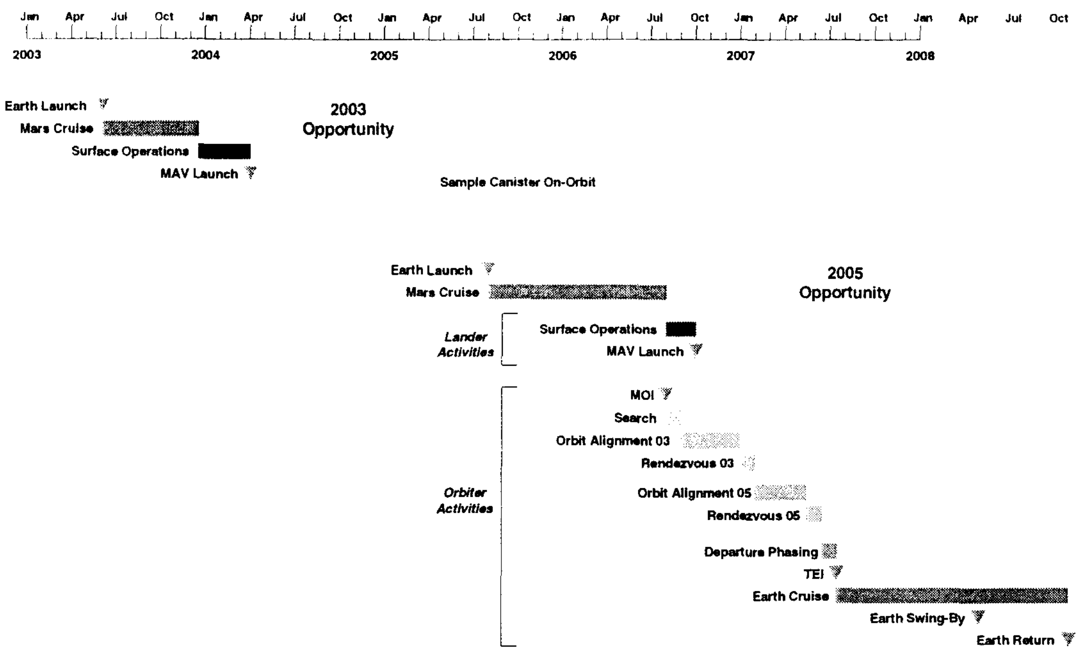
After touchdown, the 2003 lander will deploy a six-wheeled rover that will survey the local terrain, extract core samples from selected rocks, and deliver the cores back to a sample canister attached to the end of a small, two-stage rocket mounted to the deck of the lander. At the conclusion of the surface mission, this Mars Ascent Vehicle (MAV) will lift-off and insert the orbiting sample canister (OS) into a low Mars orbit. The OS will stay in this orbit until it is retrieved by the CNES-provided orbiter sometime in early 2007.

In August 2005, the orbiter and second NASA-provided lander will depart for Mars. Currently, it is proposed that a single Ariane 5 provided by CNES will launch both of these two elements onto a Type-2 transfer trajectory with a Mars arrival in late-July 2006. Although the orbiter and lander will be launched together, they will separate shortly after injection and will fly to Mars as two independent spacecraft.

Upon arrival, the 2005 lander will touchdown and perform a surface mission nearly identical in concept to the one that was executed during the 2003 opportunity. Similar to its predecessor, the 2005 lander will also launch a sample canister into low Mars orbit at the conclusion of the surface mission. Although landing

1. Mission Systems Engineer, Mars Sample Return Project - Lander Office, Jet Propulsion Laboratory
2. Principal Member of the Engineering Staff, Navigation and Flight Mechanics Section (312), Jet Propulsion Laboratory
3. Mission Design Team Chief, Mars Sample Return Project, Jet Propulsion Laboratory
4. Senior Member of the Engineering Staff, Navigation and Flight Mechanics Section (312), Jet Propulsion Laboratory

Figure 1: *Mission Timeline*



sites have not been selected, the 2003 and 2005 sites are expected to be scientifically distinct to enhance the diversity of the collected samples.

The orbiter's arrival at Mars will be highlighted by the first use of aerocapture to insert a spacecraft into orbit around another planet. This technique works by targeting the orbiter to fly through the Martian atmosphere immediately upon arrival. The enormous amount of drag generated by this single pass through the atmosphere will slow the spacecraft and allow it to be captured into orbit around Mars.

After Mars orbit insertion (MOI), the orbiter will begin orbital operations to rendezvous with and capture at least one of the two sample canisters launched into orbit by the 2003 and 2005 landers. These operations must be completed by the time the Earth and Mars align for the return Type-2 transfer in July 2007. At that time, the orbiter will fire its main engine for the trans-Earth injection (TEI) burn to escape Mars and achieve an Earth-return trajectory.

Arrival at the Earth will occur in late-April 2008, but with an approach geometry that will preclude most landing sites in the Northern Hemisphere. The current trajectory proposal to achieve a continental United States landing will require an Earth fly-by in April 2008 to deflect the orbiter onto a six-month trajectory arriving back at the Earth in late-October 2008. At that time, the approach geometry will be nearly opposite of that in April, and Northern Hemisphere landing sites will be achievable. Proposed landing plans call for the orbiter to release two small capsules from its hyperbolic approach trajectory at this second Earth encounter. Each of these Earth Entry Vehicles (EEVs) will contain one of the two sample canisters captured in orbit around Mars. Immediately after release, the orbiter will perform a deflection maneuver to avoid impacting the Earth.

Flight System Synopsis

Returning samples using the Mars orbit rendezvous (MOR) mission mode will require the use of four major flight system elements. This section of the paper will present a high-level overview of the general characteristics of these systems for the purpose of facilitating the description of the mission design. Specific implementation details have yet to be finalized due to the project's early stage of development.

Lander

Ground activities on Mars currently envisioned for the baseline mission will require the MSR lander to safely deliver 400 kg to the surface of the Red Planet. Primary payload items account for 350 kg of the 400 kg allocation and will include a rover to collect samples away from the landing site, a device fixed to the lander to collect close-proximity samples, and a Mars Ascent Vehicle (MAV) to launch the samples into Mars orbit. In addition, the lander will also carry up to 50 kg of additional payload in the form of technology experiments and science packages unrelated to sample collection activities.

All of the payload will mount to the top of a hexagonal-shaped deck. In addition, all of the lander's communication antennas will also be attached to the deck. These antennas include a high-gain antenna to provide a direct-to-Earth X-band link, a S-band antenna for communications with the rover during surface operations, and an UHF antenna capable of providing a link with Mars orbiting spacecraft. Equipment attached underneath the deck include three legs to support the lander upon touchdown, 18 thrusters (three clusters of six) for terminal descent, hydrazine propellant tanks, and a thermal enclosure to house the lander's avionics. Power on the surface will be provided by two deployable, circular-shaped solar panels extending away from the deck.

On the way to Mars, the lander will be encapsulated in a conical-shaped backshell with a heatshield attached to the bottom. In total, this configuration will amount to between 1800 kg to 1850 kg on the launch pad, making it larger than any other NASA lander sent to Mars.

Rover

Although the exterior of this six-wheeled vehicle will resemble the *Sojourner* rover used by *Mars Pathfinder*, the MSR rover will be much larger and the design will be mostly new. The dimensions of this 70-kg rover will measure approximately 1.1 meters long, 1.1 meters wide, and 1.5 meters tall with its camera mast deployed. Each one of the six wheels will attach to a rocker-bogie type suspension that will allow the rover to drive over rocks nearly the height of its 20-cm-diameter wheels. At top speeds, this solar-powered vehicle will crawl along the surface of Mars at roughly 1 meter per minute.

Sample collection will be performed using a tiny drill mounted to the bottom of the rover. The baseline procedure will involve driving the rover over a selected rock, drilling into the rock, and then depositing

Figure 2: *Lander Expanded (left) and Surface (right) Configurations*

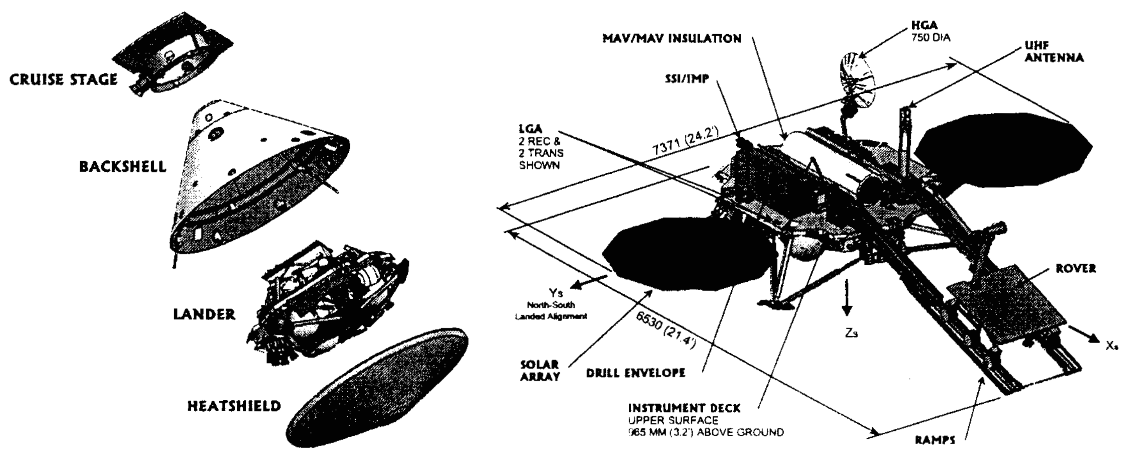
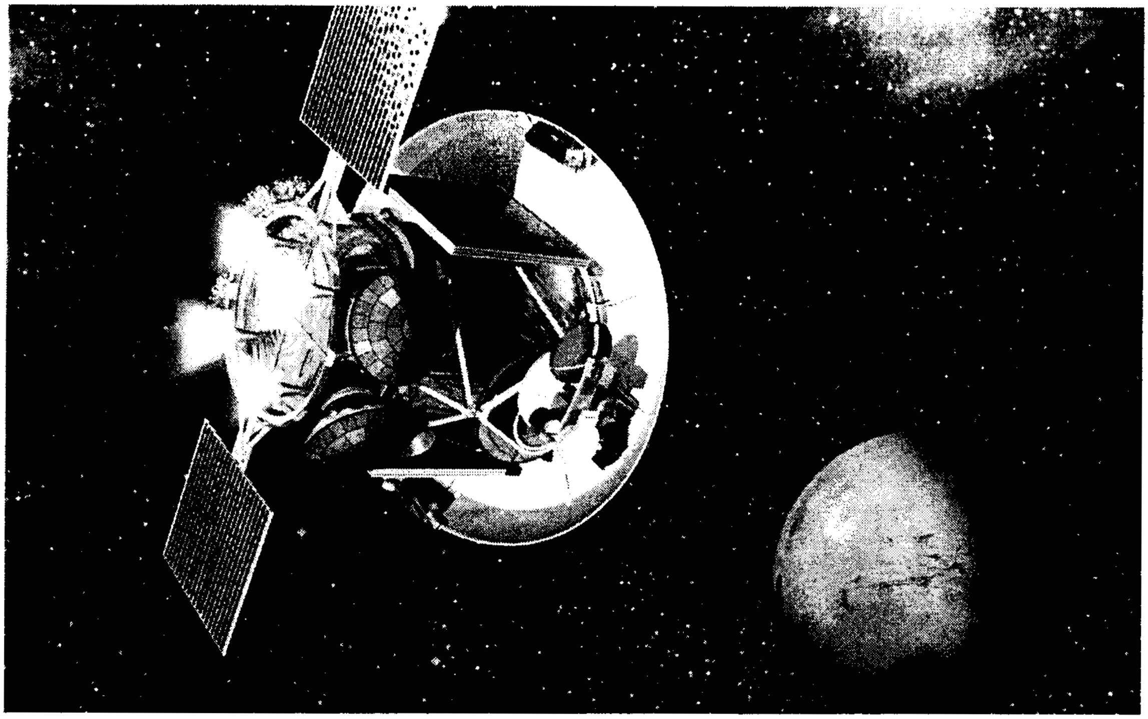


Figure 3: *Artist Rendition of the CNES-provided Orbiter*



the core sample into a small cache box next to the drill. The current design target requires a capability for the rover to extract 45 cores, each weighing about three grams. Actual collected amounts may amount to less depending on operational constraints during the mission.

Mars Ascent Vehicle (MAV)

Most of the technical specifics regarding the MAV are currently under study at this time. Currently, the baseline concept is a two-stage solid rocket approximately 1.6 meters long and 130 kg in mass. Stage 1 of the MAV will be three-axis stabilized with open-loop guidance (studies are under way to determine the need for closed-loop guidance), while Stage 2 will be unguided and spin-stabilized at about 300 r.p.m. The payload mounted to the top of the second stage will consist of a single orbiting sample canister (OS) approximately 15 cm in diameter and 3.6 kg in mass. This OS will contain the samples collected by the lander and rock cores collected by the rover.

Prior to departure from Earth, the MAV will be mounted horizontally to the top of the lander deck. At the conclusion of the surface mission at Mars, a drive mechanism on the lander will elevate the MAV to a vertical orientation for lift-off. The lander will serve as the MAV's launch pad and is not expected to functional after lift-off. A successful orbital injection by the MAV will place the OS into a circular orbit around Mars with a 600 km altitude (± 100 km dispersion), and inclination of 45° (± 1° dispersion). Trade studies are currently under way to examine the cross-system impacts of reducing the MAV's target to the 500 km regime. These impacts are expected to be a lower MAV mass, but higher ΔV required for the orbiter to rendezvous with the OS.

Orbiter

With a launch mass allocation of 2700 kg, this CNES-provided orbiter will be one of the largest interplanetary spacecraft in history. Most of the launch mass will consist of the enormous amount of propellant needed to complete this mission. In total, the orbiter will carry more than 3,250 m/s of ΔV. Of this amount, the vast majority will be consumed during the rendezvous to capture the OS launched by the two landers (550 m/s) and the trans-Earth injection burn (TEI) to escape Mars (~2,400 m/s). Significant additional propellant mass was saved by the choice to baseline aerocapture for Mars orbit insertion (MOI) rather than the traditional rocket-insertion approach.

Currently, two French aerospace companies are conducting preliminary studies on the orbiter's design. Although the specifics of this design will depend on the selection of the contractor early in the year 2000, JPL and CNES have already defined high-level characteristics as guidelines. For example, the orbiter is currently envisioned as a two stage vehicle consisting of a cruise stage and second stage. The cruise stage will primarily provide solar power for the orbiter on the way to Mars and will be jettisoned prior to atmospheric entry for aerocapture. Stage two will enter Mars orbit protected by a heatshield and then will perform the rendezvous, TEI burn, and Earth return. Similar to the line of NASA orbiters dating back to *Mars Global Surveyor,* this French orbiter will also utilize gimbaled solar panels for power and a high-gain, X-band antenna for Earth communication.

During the rendezvous phase of the mission, the orbiter will rely on a NASA payload of sensors and mechanisms. Some of the payload will include radio direction finder (RDF) antennas to locate the OS, a laser ranger (LIDAR) to provide navigation data for the terminal phase of rendezvous, a funnel-shaped capture cone to "scoop up" the OS, and two Earth entry vehicles (EEVs) that will contain the OS for their trip to Earth and will protect them through atmospheric entry and landing. The proposed EEV design will utilize a blunt-shaped conical structure with a low ballistic coefficient for low terminal velocity without the aid of parachutes. Landing will be cushioned by crushable material to limit the deceleration to about 1000 Gs.

Mission Design for the 2003 Opportunity

The first of two parts of the Mars Sample Return mission will commence during the 2003 launch opportunity. During that time period, NASA will launch a single lander carrying a rover and MAV. Several phases have been defined to simplify the description of the 2003 mission: launch, Mars cruise, atmospheric descent, and surface operations. The following table contains a summary of these phases and their dates assuming a lift-off at the open of the launch period.

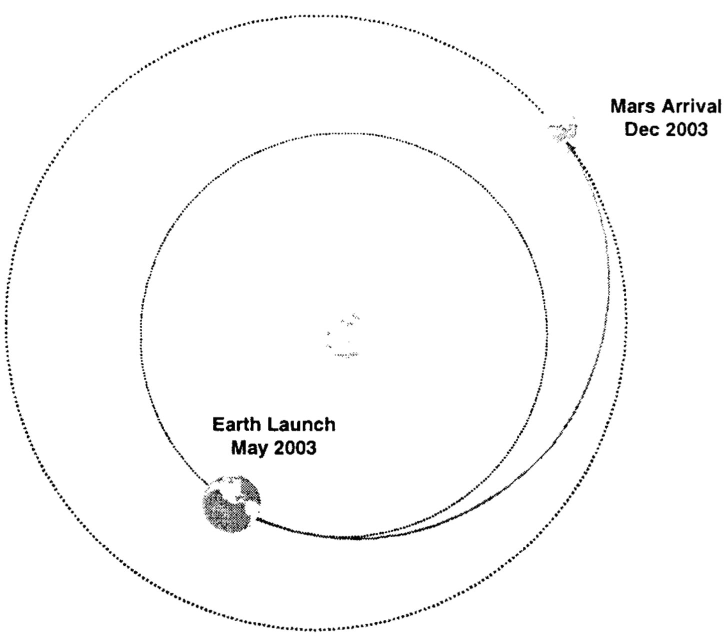
Table 1: ***Overview of 2003 Mission Phases***

Phase	Dates			Comments
Launch	27-May-03			Starts at lift-off and ends at the time of spacecraft separation from the launch vehicle.
Mars Cruise	27-May-03	to	18-Dec-03	From launch vehicle separation to the atmospheric entry point at a Mars radius of 3522.2 km.
Atmospheric Descent	18-Dec-03			From Mars entry to touchdown on the surface. Includes hypersonic flight through the atmosphere, parachute deploy, and terminal descent on thrusters.
Surface Operations	18-Dec-03	to	mid-Mar-04	Approximately 90 days to gather samples, ends with the lift-off of the MAV.

Launch Phase

Under current proposals, the 1850-kg lander will be launched by an intermediate class launch vehicle such as the Delta 3 or Atlas 3A from the Cape Canaveral Air Station in Florida. The baseline launch period for this opportunity was chosen to minimize C3 and spans 21 days from 27 May 2003 to 16 June 2003, inclusive. During the period, the C3 will reach a maximum value of 9.3 km^2/s^2 at the open and close. Due to the fact that intermediate class launch vehicles are expected to deliver over 1850 kg to a C3 of 18 km^2/s^2, a significant amount of excess performance will be available.

Figure 4: ***Trajectory Plot for 2003 Mission Opportunity***



This excess capability may be spent on optimizing the landing date with respect to the landing site latitude. To first order, power generation will be optimal if the lander touches down at a site with a latitude roughly equal to the latitude of the Sun at the time of landing. For example, a launch at the open of the period on 27 May 2003 will cause the lander to arrive at Mars on 18 December 2003. On that day, Mars will be halfway between northern winter and spring (Ls = 318°), and the optimal landing latitude will be near 16° south. If a more equatorial landing site is desired for scientific reasons, solar power generation capabilities of the lander will be better with a launch in late-June 2003 to achieve an arrival at the Martian vernal equinox (Ls = 0°) in early-March 2004.

Excess launch vehicle capability will currently allow the lander to arrive as early as 22 November 2003 (Ls = 303°) and as late as 4 March 2004. Without arrival date optimization for power considerations, the lander will still have the capability to land in a band from 15° south to 5° from a favorable power situation perspective.

Mars Cruise Phase

If the baseline launch period is utilized, cruise will last between 203 and 205 days as the lander travels to Mars on its ballistic Type-1 trajectory. A launch at the open of the launch period on 27 May 2003 will correspond to a landing on 18 December 2003, while a launch at the close of the period will correspond to a 4 January 2003 landing.

During cruise, the lander will execute five Mars cruise maneuvers (MCMs) to refine its trajectory. The first will occur as early as L+ 10 days and will primarily correct for dispersions in the trajectory caused by launch injection errors. At the other end of cruise, a small MCM may occur as late as 12 hours prior to atmospheric entry to ensure a flight-path angle uncertainty of no greater than ± 0.1°. Although the exact breakdown of MCM ΔVs will not be known until a launch covariance analysis is performed later this year, the mission design team has allocated 30 m/s to cover these maneuvers. This number was derived from past experience with similar launch vehicles.

By convention, Mars cruise will end when the lander reaches the atmospheric entry interface point at a Mars radius of 3522.2 km. Roughly 20 minutes prior to entry, the lander will slew to align the heatshield in the direction of the velocity vector. The cruise stage containing the cruise solar panels will be jettisoned at five minutes prior to entry. From this point in time until touchdown and deployment of the surface solar panels, the lander will rely on internal batteries for power.

Atmospheric Descent

This phase of the mission is internally referred to as EDL (entry, descent, and landing). Unlike the *Mars Pathfinder* and *Mars Polar Lander* spacecraft that utilized unguided ballistic EDL profiles, the MSR lander will be required to reach its designated landing site to within 10 km. In order to achieve this accuracy, the lander will be designed with an offset center of gravity to achieve a 0.18 L/D ratio, and will utilize roll thrusters to continually adjust its lift profile to compensate for variation in atmospheric density. Lower in the atmosphere, a "lift-up" phase will be executed for about one minute to bleed off excess energy. This maneuver will be needed to ensure a safe landing due to the large ballistic coefficient of the lander.

A 20-meter diameter parachute derived from the *Viking* lander design will be deployed once the lander has slowed to a supersonic velocity of 500 m/s (~Mach 2). Pressurization of the terminal descent propulsion system and jettison of the heatshield will quickly follow. At an altitude of about 4.5 km, the landing radar will be activated. Terminal descent thrusters will then fire to slow the lander to a soft touchdown with a residual vertical velocity of roughly 2.5 m/s. Upon touchdown, the landing legs are designed to crush slightly in order to help absorb shock.

Surface Operations

The first order of business after touchdown will be the deployment of the two solar panels. A rapid and successful deployment will be essential because the Mars approach geometry will constrain the landing to occur at about 14:00 Mars local time (MLT) and the lander's batteries will require recharging by sunset in order for the spacecraft to survive the first night. Unfortunately, the first use of the high-gain antenna for Earth communications cannot occur until the lander performs necessary precursor activities such as deployment of the panels and gyro-compassing for attitude determination. Due to the fact that these activities may take over an hour and Earth set will occur roughly 30 minutes after landing, no ground-based commanding will occur on the first sol, and all downlink of engineering telemetry and diagnostic images will occur at 40 bps over the low-gain antenna.

Primary activities on Sol 2 will consist of deploying the rover's camera mast and obtaining initial panoramic imaging. From its high vantage point 1.5 meters above a rover that will be sitting on top of the lander deck, the camera will obtain a 360° image of the landing site and its vicinity. This panorama will aid the flight team in determining whether to deploy the rover ramps in the lander's forward or reverse direction. An analysis of the Sol 2 images will lead to the deployment of the ramps on Sol 3, followed by rover drive-off down the ramps and on to the Martian soil on Sol 4.

Rover sampling activities will be divided into three different traverses. On each traverse, the rover will drive away from the lander, drill core samples out of selected rocks, return to drive back up the lander ramps, and then deposit the samples into the OS mounted at the top end of the MAV. Although reference scenarios for these traverses are still under development, it is anticipated that the first one will be short and of a "rapid grab" nature. The second and third traverses will be more ambitious with the rover traveling up to 200 meters away from the lander. This type of graduated scheme will ensure that some samples are immediately collected to guard against unlikely, but possible spacecraft contingencies.

At the end of the 90-sol design lifetime of the lander, the ground team will command the MAV lift-off sequence. Today, it is impossible to specify the amount of samples deposited in the OS at the time of MAV launch. Although the OS will be designed to store at least 500 grams of samples, the actual amount collected by the combined efforts of the rover and lander-based collection device will depend on the performance of the hardware under varying environmental conditions.

For an Earth departure at the open of the launch period in late-May 2003, the MAV launch will occur at the conclusion of the surface mission sometime during mid-March 2004. After injection into low-Mars orbit, the OS will wait for several years until it is captured by the CNES-provided orbiter in late 2006 or early 2007.

Mission Design for the 2005 Opportunity (Lander)

Both the 2003 and 2005 lander spacecraft will be built from the same set of plans with only minor variations between the two. Conceptually, both missions will also share many similarities in their manner of execution. As a consequence, this section of the paper will highlight some of the major differences between the two rather than repeating the description of the entire mission sequence. The following table contains a summary of the major phases of the 2005 lander mission assuming a lift-off at the open of the launch period.

Table 2: *Overview of 2005 Lander Mission Phases*

Phase	Dates			Comments
Launch	10-Aug-05			Starts at lift-off and ends at the time of spacecraft separation from the launch vehicle. Lander is launched on the same vehicle as the orbiter.
Mars Cruise	10-Aug-05	to	24-Jul-06	From launch vehicle separation to the atmospheric entry point at a Mars radius of 3522.2 km.
Atmospheric Descent	24-Jul-06			From Mars entry to touchdown on the surface. Includes hypersonic flight through the atmosphere, parachute deploy, and terminal descent on thrusters.
Surface Operations	24-Jul-06	to	8-Oct-06	Surface stay time shorter than the lander 90-sol design life due to the start of solar conjunction in October 2006.

One of the major differences between the two lander missions involves the proposed launch method. Unlike the 2003 lander that will be launched by itself from Cape Canaveral on an American rocket, the proposed method for the 2005 lander will be a launch on the same CNES-provided Ariane 5 with the orbiter. This launch vehicle can deliver a total of 5200 kg to the required C3 of 18 km^2/s^2. Within the 5200 kg allotment, the MSR project has allocated 2700 kg to the orbiter, 1800 kg to the lander, and 700 kg to adapters and the cylindrical-shaped canister that will separate the two launch spacecraft inside the payload fairing. Because the 2005 lander will have a launch allocation of 50 kg less than the 2003 lander, a reduction in payload mass delivered to the Martian surface may be necessary.

In addition to the possible payload reduction in 2005, another significant difference between the two missions is that the 2005 lander will arrive at Mars shortly before the northern summer solstice (Ls = 83°). This arrival season will dictate a landing latitude band between 5° north and 25° north in order to achieve a favorable profile from the perspective of solar power generation. Although the Ariane 5 is a more powerful booster than the intermediate-class rockets proposed for 2003, excess performance will not be available to tune the arrival date because the 2005 launch opportunity will require significantly more departure energy than the 2003 opportunity.

The other major mission design difference between the two lander missions is the estimated duration of surface operations. If the 2005 lander departs Earth at the open of the launch period on 10 August 2005, Mars arrival will occur on 24 July 2006. In this best-case scenario, a 90-sol surface mission may not be possible because solar conjunction will occur in mid-October 2006 as Mars passes behind the Sun as seen from Earth. Loss of communications may occur as early as Sol 76 at the beginning of October and may not be reestablished until the end of conjunction in early November.

Although the lander will be designed to survive for up to 28 days without commanding, flight operations management may be forced to launch the MAV prior to conjunction rather than risk a hardware failure near the end of the lander's design life. This "early launch" scenario will cut into the rover's sample collection schedule by about 15 sols in the best case, and by nearly half in the worst case of an arrival (26 August 2006) corresponding to a departure at the end of the launch period.

Mission Design for the 2005 Opportunity (Orbiter)

Several phases have been defined to simplify the description of different periods of mission activity for the orbiter: Mars cruise, Mars approach, orbit insertion, rendezvous, departure, and Earth cruise. The following table summarizes the phases and their dates assuming a lift-off at the open of the launch period on 10 August 2005. In the table, the ΔV budget numbers for each mission phase do not include an allocation for gravity loss or attitude control.

Table 3: *Overview of 2005 Mission Phases*

Phase	ΔV Budget	Dates			Comments
Launch	n/a	10-Aug-05			Starts at lift-off and ends at the time of spacecraft separation from the launch vehicle.
Mars Cruise	55 m/s	10-Aug-05	to	24-Jun-06	From launch vehicle separation to MOI- 30 days
Mars Approach	50 m/s	24-Jun-06	to	24-Jul-06	From MOI- 30 days to the atmospheric entry point for aerocapture. NetLander deployment during this time.
Orbit Insertion	140 m/s	24-Jul-06	to	28-Jul-06	Includes the MOI via aerocapture and the associated post-capture activities and trim maneuvers designed to prepare the orbiter to start the rendezvous process.
Rendezvous	550 m/s	28-Jul-06	to	16-Jun-07	Allocation of approximately one year for the rendezvous with and capture of two orbiting samples.
Departure	2370 m/s	17-Jun-07	to	21-Jul-07	Starts with four weeks to align the orbit node with the departure asymptote for Earth and ends after the TEI burn.
Earth Cruise	85 m/s	21-Jul-07	to	13-Nov-08	From after TEI to two weeks after EEV landing. Proposal to include Earth gravity assist on 29-Apr-08 followed by EEV landing on 30-Oct-08.

Launch Phase

As described in the previous section on the 2005 lander mission, the current proposal for launch is to utilize a single CNES-provided Ariane 5 booster for both the 2005 lander and orbiter. The primary launch period spans 21 days from 10 August 2005 to 30 August 2005, inclusive. Although the current baseline launch window strategy will employ one instantaneous launch opportunity for each day in the launch period, actual lift-off times have not yet been calculated.

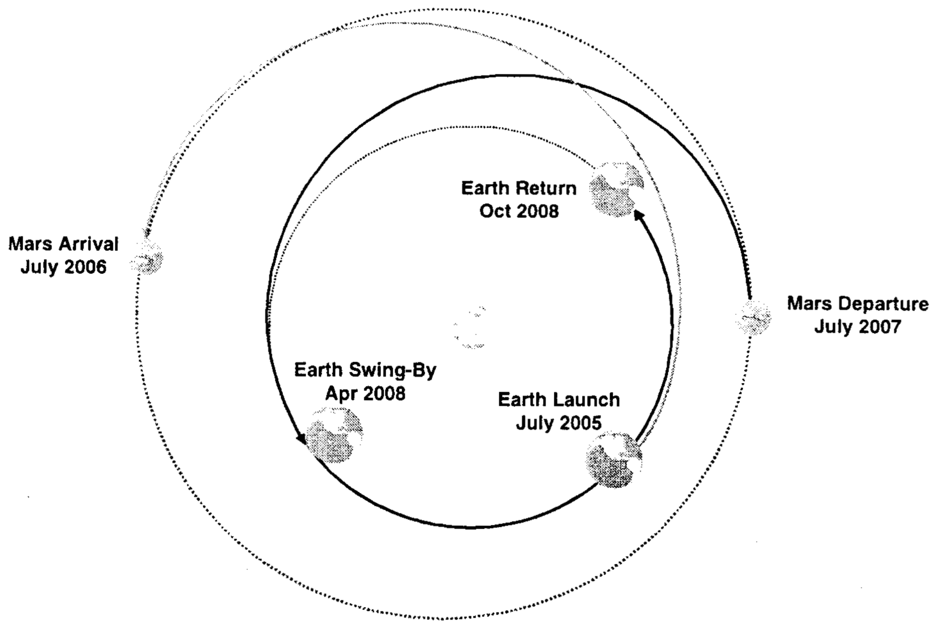
Mars Cruise Phase

Mars cruise covers most of the ballistic flight as the orbiter travels from Earth to Mars. The spacecraft will take between 348 and 361 days to reach the Red Planet on its Type-2 trajectory depending on the Earth departure date within the 21-day launch period. A launch at the open of the period on 10 August 2005 will correspond to a Mars arrival of 24 July 2006, while a launch at the close on 30 August 2005 will result in an arrival on 26 August 2006. By definition, the Mars cruise phase will end 30 days prior to Mars arrival.

Post-Separation Activities

Shortly after separation from the upper stage of the Ariane, the orbiter will deploy its solar panels, establish inertial attitude knowledge and control, and initiate the downlink of engineering telemetry to the Earth. All of these initiation and survival activities will be performed autonomously because uplink to the

Figure 5: ***Trajectory Plot for 2005 Mission Opportunity***



spacecraft may not be available until 30 minutes to one hour after separation. However, the spacecraft must begin downlink fairly rapidly after separation in order to facilitate the two-way lock-up and tracking of the orbiter's signal by the Deep Space Network (DSN). Current requirements call for the orbiter to begin transmission within 10 minutes after separation.

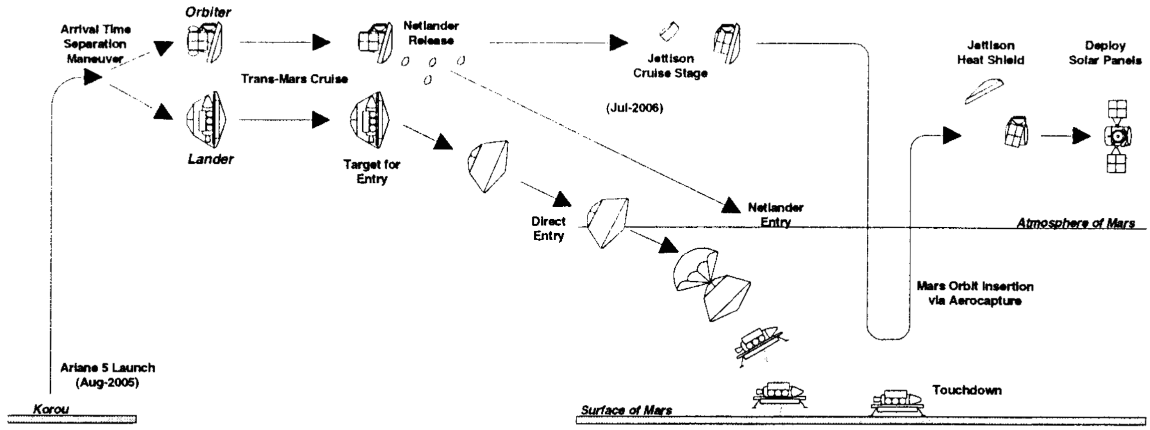
At the time of DSN initial acquisition, the Sun-probe-Earth (SPE) angle will be approximately 110°. Consequently, the onboard antenna used during this time period must have a field of view broad enough to maintain the link while the orbiter points the solar panels in a direction close enough to the Sun for adequate power generation. This initial acquisition attitude has not yet been determined, but will be supplied by the launch vehicle's upper stage if the orbiter's ability to perform an inertial slew and hold can not be established rapidly after separation.

Cruise Activities

During cruise, the orbiter will execute five Mars cruise maneuvers (MCMs) to refine its trajectory. The first one will occur as early as L+ 10 days, and the last one may occur as late as MOI- 30 days. The exact MCM strategy is not yet known because an analysis of the expected Ariane 5 launch dispersions has not been completed at this time. However, based on past experience with launch vehicles employing inertially guided upper stages, the mission design team has allocated 55 m/s of ΔV for MCMs. Of this number, 30 m/s will be used for trajectory corrections, and 25 m/s will be used to adjust the orbiter's arrival time to differ from the lander by at least 24 hours. At this time, it has not been determined whether the lander or orbiter will arrive first.

With the exception of maneuver execution, the orbiter will always fly in an attitude capable of supporting simultaneous communications with the Earth and adequate power generation by the solar panels. This constraint is necessary because a continuous signal transmission from the spacecraft will be required to support navigation for key events. Although the cruise attitude has not yet been specified, it may change several times during the year-long journey to Mars as the SPE angle decreases from 110° post launch to 18° just prior to MOI.

Figure 6: *Mission Schematic for 2005 Opportunity (1 of 4)*



Mars Approach Phase (Orbiter)

Approach will begin at MOI- 30 days and will last until the orbiter enters the Martian atmosphere at the start of aerocapture. The major activity during this phase will be the release of the four CNES-provided NetLanders that will ride piggyback on the orbiter to Mars. These NetLanders will serve as surface stations for scientific investigations independent of the sample return operations.

During each NetLander deployment cycle, the orbiter will perform a targeting maneuver to alter its trajectory to the precise aim point, perform a trim maneuver to refine the accuracy of the targeting maneuver, and then release the NetLander. Each one of these cycles will take four days to complete with the first release occurring near MOI- 24 days. At MOI- 10 days, the orbiter will perform an aerocapture targeting maneuver (ATM) to deflect the trajectory back toward the aim point needed to support atmospheric entry.

Project requirements dictate that orbiter activities scheduled between MOI- 10 days and MOI are strictly limited to those that directly support a successful aerocapture. Some of these events include a small, but final, trim maneuver at MOI- 6 hours to achieve the required flight path angle accuracy at the atmospheric entry, and the jettison of the orbiter cruise stage several minutes prior to entry. Analysis performed to date indicates that a successful aerocapture requires the orbiter to be delivered to the atmospheric entry point (radius of 3522.2 km from Mars) with a 3σ flight-path angle accuracy of $\pm 0.1°$.

Similar to Mars cruise operations, the orbiter will always fly in an attitude capable of supporting simultaneous communications with the Earth and adequate power generation by the solar panels. The exception to this rule will be maneuver execution and NetLander deployments.

Orbit Insertion Phase

The orbit insertion phase will begin when the orbiter reaches the Mars atmospheric interface boundary defined at a radius of 3522.2 km on the hyperbolic approach trajectory. This phase is defined to include the aerocapture MOI event, the burn to raise periapsis out of the atmosphere at the first apoapsis after MOI, and the orbit trim maneuvers required to remove the effects of atmospheric variability and guidance dispersions on the post-aerocapture orbit.

Mars Orbit Insertion

Aerocapture will be targeted to produce a capture orbit with an inclination of 45° and apoapsis altitude of 1400 km. The target inclination was chosen as the lowest possible given the declination of the hyperbolic approach asymptote. Lower inclination values are desirable because they tend to maximize rendezvous performance by minimizing ΔV. At the conclusion of the 2003 lander mission, the OS will be placed into a 45° orbit by the MAV in anticipation of the orbiter achieving this inclination.

The post-aerocapture altitude was selected after examining Monte Carlo runs that calculated the probability of phasing resonance between the orbiter and 2003 OS, accounting for dispersions in both aerocapture and MAV injection accuracy. The Monte Carlo runs indicated only a 1% probability of phasing resonance with a post-aerocapture apoapsis altitude of 1400 km. Resonance is extremely undesirable effect because the OS search scenario is almost impossible to execute if both spacecraft are always on different sides of the planet.

Current analysis from CNES indicates that achieving the capture orbit goals will require approximately four minutes of flight deep in the atmosphere with the periapsis of the inbound hyperbola targeted to an altitude of about 43 km. During these four minutes, the orbiter will reach altitudes as low as 35 to 40 km, and will fire thrusters as needed for bank angle adjustments to account for atmospheric dispersions and inclination control. CNES is currently investigating the use of a predictor-corrector type guidance algorithm to control the orbiter during atmospheric flight.

Shortly after exiting the atmosphere, the heatshield will be jettisoned to avoid the transfer of thermal energy from the shield back to the spacecraft. Approximately one hour later, the orbiter will arrive at the first apoapsis of the post-aerocapture orbit. At that time, the spacecraft will execute an aerocapture termination burn (ACX) to raise periapsis out of the atmosphere.

The implementation philosophy of ACX has not yet been determined. One possible option will involve loading a pre-computed maneuver prior to MOI that is not updated before ACX. This option is simple, but may introduce sizeable dispersions in the post-ACX orbit because the maneuver magnitude must be large enough to raise periapsis under worst case conditions. Another more complicated, but also more accurate option will utilize the orbiter's computer to re-compute the maneuver based on IMU integration of the trajectory during atmospheric flight. In either case, the maneuver will be performed autonomously.

An important design goal will be for the orbiter's transmitter to be powered on for as much time as possible between atmospheric entry and the conclusion of ACX. Although the receipt of telemetry may be impossible during part of this time, one-way Doppler tracking of the carrier signal will provide valuable data that will allow the navigation team to monitor the orbiter's trajectory in realtime. As important, the carrier signal will also provide a clear indication that the spacecraft is still functional. After ACX, the orbiter will operate in a mode that will allow simultaneous communications with the Earth and adequate power generation by the solar panels.

Post-Aerocapture Activities

During the first few days following ACX, the operations team will perform health monitoring activities and software parameter updates needed for the transition from cruise to orbital operations. In addition, the orbiter may perform several trim maneuvers (OTMs) to refine the orbit for the initiation of the rendezvous phase. The current target requirement at the end of the orbit insertion phase is a periapsis altitude of 250 km ± 20 km, and an apoapsis altitude of 1400 km ± 100 km. If the post-ACX orbit falls within this range, then OTMs will not be required.

Rendezvous Phase

Current project requirements dictate a transition from the insertion to rendezvous phase within seven days of MOI. This transition point will occur when the target 250 km x 1400 km orbit has been achieved within the allowable dispersion range, and the orbiter has been declared ready to commence orbital operations.

Search: 2003 OS

Step one in the rendezvous phase will be the search for the sample canister (OS) launched by the 2003 MAV. This detection and orbit determination of the 2003 OS will be accomplished by using the orbiter's radio direction finder (RDF) to listen for the canister's solar powered beacon. The orbiter, however, is not required to have the capability to autonomously perform orbit determination calculations using RDF data gathered during the search phase. Instead, the information collected by the search sensors will be transmitted to Earth and processed by a ground-based navigation team.

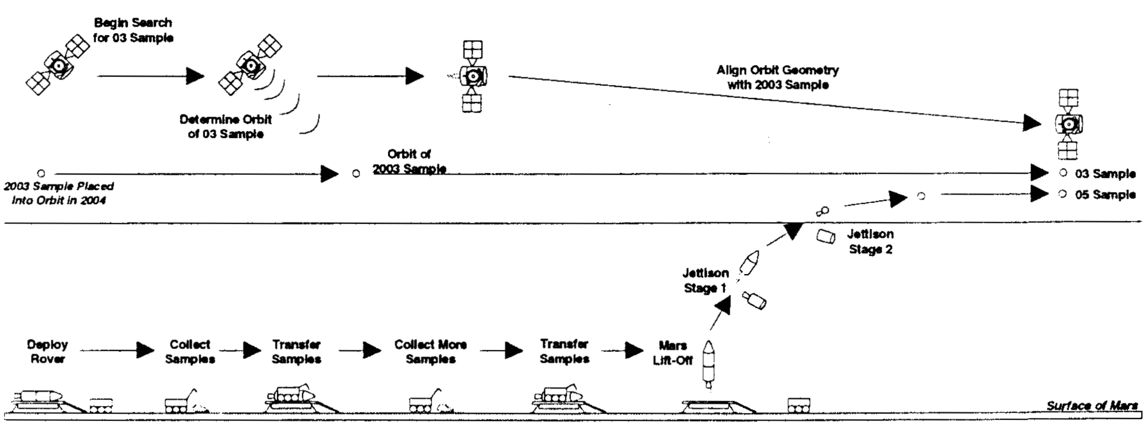
During the search, the spacecraft will spend a significant portion of the daylight side of each orbit in an attitude conducive to search operations. Preliminary analysis indicates that one acceptable way to perform the search will involve inducing a slow pitch profile to keep the RDF antennas pointed along the inertial velocity or anti-velocity direction. Unfortunately, flying the orbiter in this type of profile is equivalent to a constant nadir point and will present a difficult design challenge in terms of balancing pointing needs for solar power generation and communicating with the Earth. Another option currently under study by the mission design team is to examine the impacts of performing the search while keeping the orbiter inertially pointed at the Earth. This type of attitude is easier for operations, but less favorable in terms of RDF pointing geometry.

Intermediate Rendezvous: 2003 OS

Once the 2003 OS has been located, the orbiter will perform a series of maneuvers to align its orbit node, inclination, and semi-major axis to match those of the canister's orbit in a process called intermediate rendezvous. During this period, the use of drift orbits and gravity harmonics for orbital alignment will be used to minimize propellant consumption. Current analysis indicates that this type of strategy will require about 8 to 10 maneuvers to implement.

The goal of these maneuvers is to deliver the orbiter to an orbit co-elliptical with the 2003 OS at a position below and behind the canister. Under ideal conditions, the OS will be in an orbit 600 km x 600 km altitude with an inclination of 45°. However, dispersions from the 2003 MAV launch may cause both a semi-major axis error of ± 100 km (3σ), and an inclination error of ± 1° (3σ). Extrapolation of current analysis by the MAV design team indicates that these dispersions may cause periapsis altitudes as low as 390 km and apoapsis altitudes as high as 875 km in the extreme.

Figure 7: ***Mission Schematic for 2005 Opportunity (2 of 4)***



Similar to the navigation paradigm employed during the search phase, all orbit determination and maneuver calculations will be performed by a ground-based team as opposed to an onboard system. Therefore, the spacecraft will spend much of its time during intermediate rendezvous in an Earth-pointed attitude to maximize the amount of tracking data gathered by the DSN.

Another important concept for the design team to factor into the orbiter design is that Mars will pass behind the Sun as viewed from the Earth during the middle of the 2003 OS intermediate rendezvous phase. This period of solar conjunction is expected to last about four weeks starting on 8 October 2006. During conjunction, the orbiter will be required to function autonomously because the receipt of commands from the ground will be difficult. The rendezvous flight plan will not require maneuvers while in conjunction in order to simplify this situation.

Terminal Rendezvous: 2003 OS

After the completion of intermediate rendezvous, the orbiter will be in a co-elliptic orbit two km below and TBD km behind the OS. This position will cause the orbiter to close the downtrack distance to the canister at a rate of TBD km per day. Two days later, the orbiter will perform two small burns (approximately 0.3 m/s magnitude, each) to transfer to a new co-elliptic orbit TBD km below the OS. After the transfer, the closure rate will drop to TBD km per day.

Once the orbiter has closed the distance to the OS to less than 5 km, the flight team will activate the laser radar (also known as LIDAR for light detection and ranging) and attempt to establish laser lock on the canister. During the last hundred meters of terminal rendezvous, the LIDAR will be the prime instrument to provide the rendezvous computer with information regarding the state of the OS. The goal will be to lock onto the OS by the time of the terminal phase initiation (TPI) maneuver. This autonomously executed burn of approximately 0.1 m/s will take place at a range of about 1 km and will transfer the orbiter from its co-elliptic state to the same orbit as the OS, but at a position 80 meters in front of the canister. Current analysis indicates that TPI can be computed and executed on RDF angle data alone in the event that LIDAR lock has not yet been achieved.

At the 80 meter position on the positive V-bar relative to the OS, the orbiter will stationkeep for at least two orbits. This time will allow the ground team to make a final assessment of the orbiter's performance

Figure 8: *On-Orbit Operations Timeline*

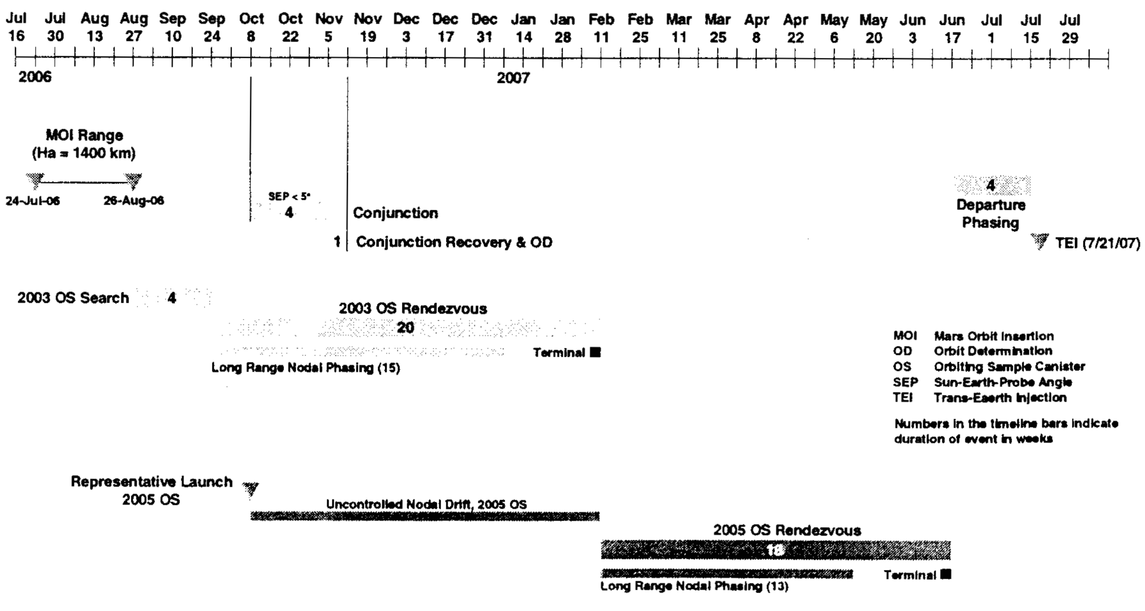
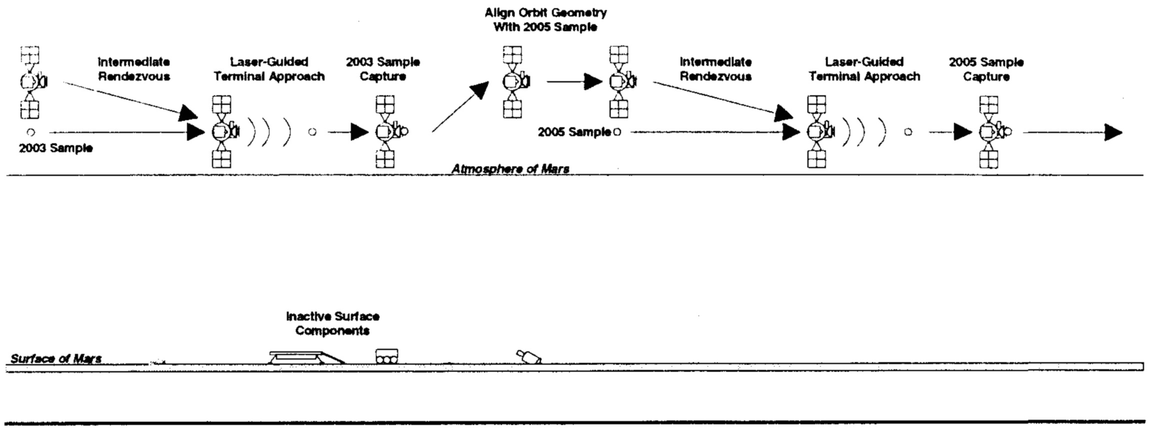


Figure 9: ***Mission Schematic for 2005 Opportunity (3 of 4)***



and to issue a final GO/NO-GO command for full autonomous operations. Once the GO has been issued, the orbiter will automatically close the remaining 80 meters and capture the OS. The operations from GO to capture is expected to take about 16 minutes. Due to light-time delay considerations, this final phase must be performed autonomously.

Intermediate Rendezvous: 2005 OS

Sometime during the intermediate rendezvous operations to capture the 2003 OS, the 2005 surface elements will complete their mission. At that time, the lander will launch its MAV to inject the 2005 OS into a 600 km x 600 km altitude orbit with an inclination similar to that of the 2003 OS. In order to optimize on-orbit time usage, search and orbit determination operations for the 2005 OS will be performed in parallel with the 2003 OS intermediate rendezvous. Such a scheme is possible because most of the 2003 OS intermediate phase will consist of unused time as the orbiter waits for the proper time to perform maneuvers.

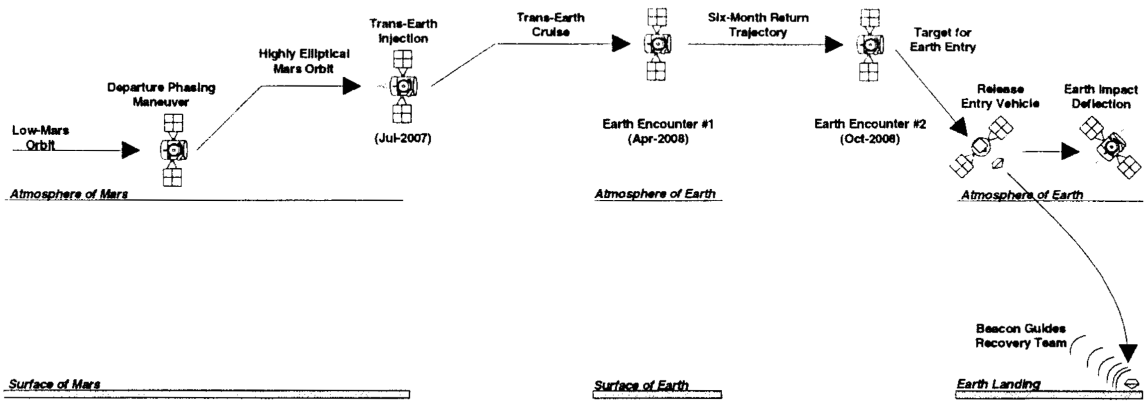
Propulsive maneuvers that will initiate the rendezvous with the 2005 OS will begin almost immediately after the capture of the 2003 OS. The first step in this process will be the execution of a series of maneuvers that will match the inclination, node, and semi-major axis of the orbiter and 2005 OS. This maneuver series is identical in concept to the intermediate phase maneuvers executed during the 2003 rendezvous and will deliver the orbiter to a an orbit co-elliptical with the 2005 OS at a position 2 km below and TBD km behind the canister. The following table provides a description of the 2005 OS intermediate rendezvous maneuvers and their respective magnitudes.

In total, the orbiter will carry 480 m/s to cover the intermediate rendezvous maneuvers for both the 2003 and 2005 canisters. This amount corresponds to enough to cover 99% of the expected scenarios when the ΔV values from both intermediate phases are statistically combined. The mean value for this combination is 346 m/s with a standard deviation of 44 m/s.

Terminal Rendezvous: 2005 OS

After the conclusion of the 2005 intermediate phase, the orbiter will perform an autonomously guided terminal phase from its initial co-elliptical position to the capture of the canister. The technical principles, flight mechanics, and spacecraft constraints governing this phase will be identical in concept to those governing the 2003 terminal phase. In total, the orbiter will carry 40 m/s worth of propellant for the two terminal phases. This amount ΔV will provide for two terminal attempts per canister with an estimated cost of 10 m/s per attempt.

Figure 10: *Mission Schematic for 2005 Opportunity (4 of 4)*



Departure Phase (Orbiter)

Before the orbiter performs the maneuver to escape Mars and initiate an Earth return trajectory, it must wait until nodal regression rotates the orbit plane into alignment with the departure asymptote of the Earth-bound trajectory. Although the node that will match the orbit plane with the asymptote can be computed today, the node of the orbiter at the conclusion of the rendezvous phase will be essentially random. As a consequence, the nodal regression process to achieve the proper departure alignment may take anywhere from zero to slightly greater than four weeks to complete. A successful departure will require the orbiter to achieve this alignment exactly on the scheduled departure day.

The solution to this problem will involve the execution of a departure phasing maneuver (DPM) if nodal alignment occurs before the departure date. This burn will create a phasing orbit with a nodal regression rate of virtually zero by increasing the size of the original orbit from approximately 600 km circular to 600 km x 56,500 km (approximately 48 hour period). In reality, DPM will consist of three burns executed on consecutive or near consecutive orbits in order to limit gravity loss effects. The first two burns in this sequence (615 m/s each) will collectively raise the orbit to a 48-hour period, while the last burn (12 m/s) will lower periapsis to 170 km to reduce the ΔV needed for Mars escape.

After the conclusion of the DPM sequence, the orbiter will wait in the resultant highly elliptical, 48-hour orbit until 21 July 2007. On that day, the spacecraft will perform the trans-Earth injection (TEI) burn to escape Mars and achieve an Earth-return trajectory. Between DMP and TEI, the orbiter must expended enough propellant to achieve a departure energy of 10.2 km^2/s^2. Assuming the lowest possible post-rendezvous orbit (500 km index altitude), the DPM sequence and TEI maneuver will require impulsive burns magnitudes of about 1242 m/s and 1090 m/s, respectively. Total gravity losses during these burns will amount to roughly 75 m/s for an 800 N main engine thrust level.

Earth Cruise Phase

Earth cruise covers the time of ballistic flight as the orbiter travels from Mars back to Earth. The proposed baseline option involves a Type-2 trajectory from Mars leading to a first Earth encounter (E1) on 29 April 2008, a gravity assist deflection to a six-month Earth-to-Earth transfer trajectory under the ecliptic, and a landing at the second Earth encounter (E2) on 30 October 2008. This 467-day return option will allow for both a minimal energy departure from Mars and a Northern Hemisphere landing at Earth.

Cruise Activities

During the time between Mars and the first Earth encounter (E1), the orbiter will execute several Earth cruise maneuvers (ECMs) to refine its trajectory. The first one may occur as early as TEI+ 2 days, and the last one as late as late as several days prior to the encounter. In general, the earlier ECM burn magnitudes will be in the range of several meters per second to tens of meters per second, while the later burns will amount to several meters per second to tenths of meters per second.

If the proposed baseline option for the Earth cruise is chosen, the fly-by closest approach at E1 will occur at an altitude of about 30,000 km. The gravity assist from this fly-by will deflect the orbiter into a heliocentric trajectory with the same size and shape as the Earth's orbit, but slightly inclined to the ecliptic. When the spacecraft re-encounters the Earth six months later at E2, its approach will be from below the ecliptic moving from south to north. This geometry will facilitate the northern hemisphere landing.

Trajectory corrections will dominate the orbiter's mostly empty itinerary between E1 and E2. Several days after the fly-by, the spacecraft will perform a "clean-up" maneuver of about 5 m/s to correct for dispersions resulting from the gravity assist. During the remaining six months prior to E2, several additional ECMs will be performed to refine the trajectory toward the aim point for the release of the EEVs.

For planetary protection reasons, it is proposed that the orbiter maintain a trajectory that misses the Earth until several days prior to E2. At that time, the flight team will command an entry targeting maneuver to move the orbiter from a fly-by trajectory to that required for atmospheric entry. A short time later, a small "clean-up" maneuver will be executed to ensure that the trajectory achieve a flight-path angle accuracy of 12° ± 0.1° at the atmospheric entry point. Almost immediately after this maneuver, the spacecraft will release the EEVs and then perform an Earth deflection maneuver (EDM) of 15 m/s to keep from following the EEVs into the atmosphere.

With the exception of maneuver execution and EEV release, the orbiter will always fly in an attitude capable supporting simultaneous communications with the Earth and adequate power generation by the solar panels. This constraint is necessary because a continuous signal transmission from the spacecraft will be required to support navigation for key events. Although the cruise attitude has not yet been specified, it may change several times during flight as the SPE angle increases from 43 degrees post TEI to 110 degrees just prior to E1.

Conclusion

Plans for the Mars Sample Return mission have been developed that utilize Mars orbit rendezvous as the baseline mission mode. This plan will employ the launch of two landers and one return orbiter across two different mission opportunities. Many mission design challenges lie ahead including the first aerocapture attempt, the first autonomous rendezvous attempt in orbit around another planet, and the design of a robust surface operations scenario capable of semi-autonomous sample collection and transfer. Although the high-level concepts presented in this paper will reflect the general strategy in which the mission will be executed, implementation details are likely to change as the flight system design and capabilities mature and the mission design team optimizes its design to reflect the evolution of the flight system.

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