# Mars Sample Return: The Design of Low Risk Architectures

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*Abstract*—The 2011 Mars Sample Return mission objective is to acquire and deliver greater than 500 grams of material from the surface of Mars to the NASA planetary materials curatorial facility. The mission is science driven and technology enabled within the overall constraints of the Mars Exploration Program.

The MSR architecture design process strives to balance three aspects of the mission; performance, cost and risk. In addition, dependency on new, mission enabling technologies should be minimized while maximizing the ability to incorporate mission-enhancing technologies developed outside the program. Numerous flight elements necessitate a thorough understanding of element interdependencies and identification of how changes to each element ripple through the entire architecture.

Several architectures for achieving the MSR mission objective have been identified and evaluated during the past year at Lockheed Martin. Each of the architectures is feasible, with varying levels of mission risk, technology requirements, and operational flexibilities. After conducting a preliminary evaluation of these architectures, two mission designs were then studied in more detail, Libration Point Rendezvous (LPR) and Mars Orbit Rendezvous (MOR).

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## 1. INTRODUCTION

Mars Sample Return missions have been the subject of architecture studies several times over the past years. During 2001 the Advanced Programs Group at Lockheed Martin Astronautics conducted a comprehensive evaluation of the entire MSR trade space under the funding and oversight of the NASA Jet Propulsion Laboratory. Following a systematic systems engineering process, the mission architecture trade space was defined, analyzed and narrowed down first to six and then to two mission architectures. During this process a novel architecture utilizing the Mars-Sun libration point was developed. This paper summarizes the mission requirements levied on the study, the approach to reduce and balance risks, the definition and assessment of the architecture trade space, and finally a top-level description of two of the more promising architectures.

## 2. MSR OBJECTIVES AND REQUIREMENTS

The 2011 Mars Sample Return mission objective is to acquire and deliver greater than 500 grams of material from the surface of Mars to a unique NASA facility designed for handling these samples. The mission is science driven and technology enabled within the overall constraints of the Mars Exploration Program. The return of diverse samples from Mars will enable a more thorough understanding of the planet than would otherwise be achievable with remote sensing and in-situ analysis. The Mars Exploration Program has established a science baseline requiring that the total mass of samples returned by a first mission be greater than 500g; that returned samples include rock, soil and atmosphere; that sample diversity be assured by providing mobility for the sample selection and collection of no less than 1 km; and that the sample collection vehicle lands in a

50 km target zone. Additional requirements include obtaining of sample from a depth of 2 meters and the determination and documentation of the geologic setting of each sample.

Planetary protection requirements impose unique design requirements for the sample return architecture. While not formally in place, these design constraints include forward cleanliness levels of Category III for orbiters and Category IV B for landers/rovers. These cleanliness levels are driven by science requirements for life detection. Backward contamination constraints levy Category V design requirements on the Mars ascent vehicle, Earth return vehicle and Earth entry vehicle. In addition, the sample container must be sealed such that the probability of releasing particles into the Earth's biosphere is extremely low.

In addition to collecting diverse samples on Mars and retuning them to Earth in a biologically safe manner, the mission is required to carry multiple instruments to the surface of Mars for in-situ analysis of the Martian environment. Categories of investigation include radiation environment analysis, soil and dust analysis, and planetary biology experiments. Results from these activities will then feed into the design of future Mars exploration missions, leading to a potential human mission to the planet.

Finally, wherever possible the flight elements of the sample return mission should contribute to the execution of future Mars exploration missions. For example, any orbiting element must provide communications relay functions for an extended period of time, enabling multiple future surface assets (landers, rovers, probes, airplanes, etc.) to transmit their collected data to Earth. While not intended to be a design driver, there is also a strong desire for the sample return mission surface assets to survive the launch of the Mars Ascent Vehicle and conduct extended investigations of the Martian environment.

## 3. Mission Design Principles

The MSR architecture design process strives to balance three aspects of the mission; performance requirements, cost, and risk. In addition, dependency on new, mission enabling technologies should be minimized while maximizing the ability to incorporate mission-enhancing technologies developed outside the program. The multiple flight elements necessitates a though understanding of element interdependencies and identification of how changes to each element ripple through the entire architecture.

In regards to the mission architecture, the first of these three components, mission performance requirements, includes such aspects as the science quantity and quality, launch opportunity, and launch vehicle capability. In general, the launch opportunity is a fixed parameter although opportunities for a delayed launch may occur. The science quality and quantity parameters are generally increased to the detriment of the other two elements. The launch vehicle capability is also a generally fixed parameter given a family of approved vehicles. The science value of a mission is straightforward to characterize and a sensitivity to cost can be evaluated rather easily. In general, mission requirements are forcing functions, which impact the other two design parameters.

The cost of the program is another component of the mission design that is generally a forcing function once the limit has been approached. Cost occasionally will be a forcing function on science quality or quantity. Mission descope plans are often formulated to reduce science once the ceiling cost has been exceeded. Delaying the launch opportunity is generally never an option to reduce cost.

The third element, risk, is the area where the mission generally attempts to accommodate the limitations of the cost constraint, while still satisfying the mission requirements. Unfortunately, risk elements are generally the most difficult to quantify in terms of their impact on the mission. They can extend from the selection of flight hardware, through the testing of the flight system, and impact the manner in which the spacecraft is flown. However, even more basic than the subsystems within a spacecraft, the actual architecture of a mission is the first place to minimize the risk exposure of a specific mission. Methods to quantify the mission risk can be created that will lead a designer to converge on an approach that will maximize the probability of mission success.

The Mars sample return mission architecture is comprised of a number of basic flight elements that perform together to execute the mission. Understanding the interdependencies of these elements is critical to ensuring the design principles are balanced in an acceptable manner. An example of this relationship is shown in Figure 3-1. First, the sample requirements need to be defined – how much and in what configuration (dust, rocks, atmosphere, drill core, etc.). These requirements then impact the sizing of the Orbiting Sample (OS) container. Once the OS mass and volume is known, the Mars Ascent Vehicle (MAV) can be designed. After the MAV has delivered the OS to a predetermined destination, the OS must be transferred in a clean manner into an Earth Entry Vehicle (EEV) and if a rendezvous mission architecture is designed, the EEV is carried on an Earth Return Vehicle (ERV). The size of the Mars Lander is determined by its payload, which consists of the MAV, rover, and sampling equipment required to capture the samples defined in the first step. Once the size of the Lander is known, entry, descent and landing functions are

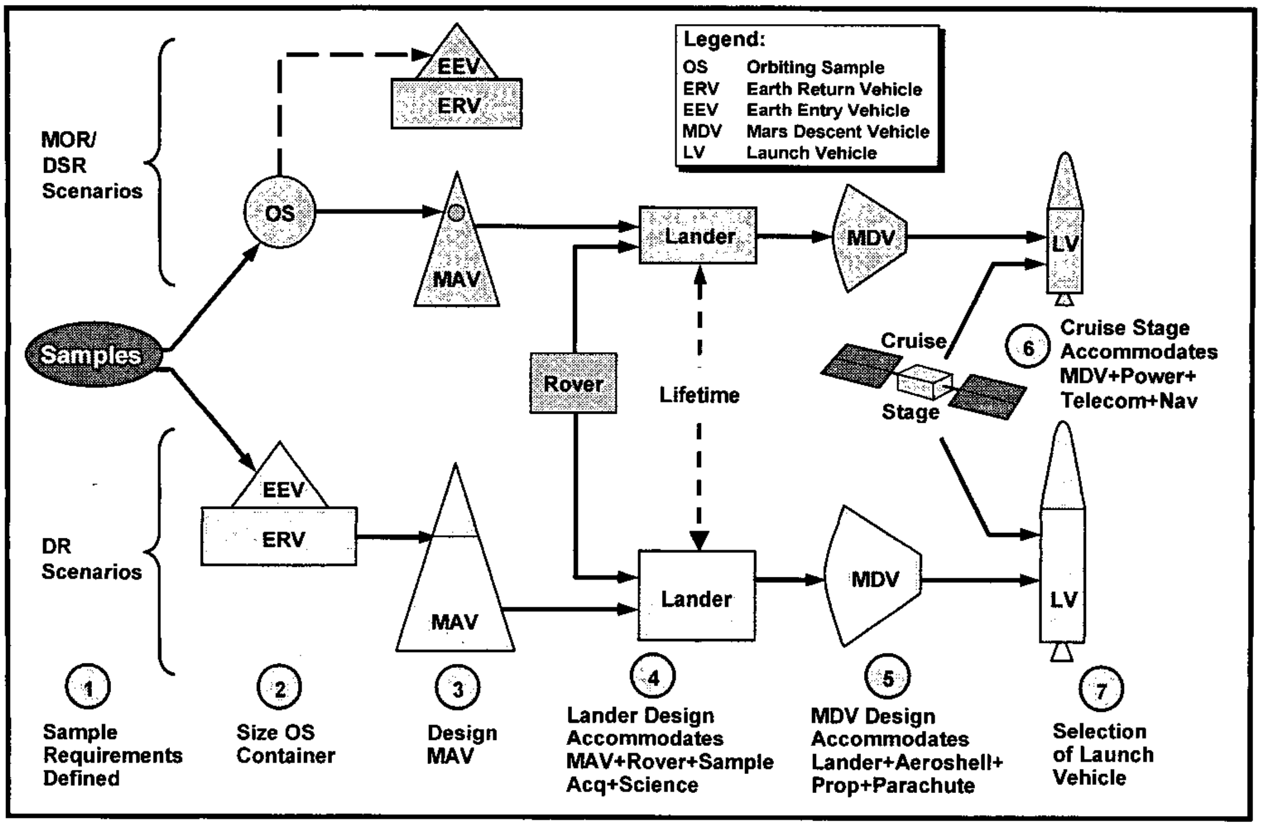


Figure 3-1 – MSR Architecture Element Interdependencies

added to create a Mars Descent Vehicle (MDV). Power, telecom, and navigation functions are then added to the MDV to arrive at a cruise stage. After all of the above elements have been defined, then a Launch Vehicle can be selected. In designing mission architectures, this process is iterated numerous times to achieve a balanced performance, cost and risk design for all the elements.

## 4. Risk Minimization Techniques

There are numerous areas where the risk of the MSR mission can be minimized by incorporating basic risk reduction techniques from the outset. These techniques include minimizing the number of flight regimes in which the system is required to operate, minimizing the number of sample transfers while satisfying planetary protection requirements to break-the-chain, and ensuring operational flexibility through functional redundancy and opportunities to reconfigure operational sequences in response to performance anomalies.

For an Earth return vehicle system, one can imagine the need for a cruise to and from Mars with an unpowered flyby as the bare minimum. Loosely capturing at Mars, and departing from a highly elliptical orbit at Mars are the next levels of complexity that one might entertain for an ERV. Propulsively deorbiting, or aerobraking into a low Mars orbit are the next logical levels of ERV risk that one can imagine. Carrying this functionality to the surface, and launching from the surface of Mars is another flight regime that will have a negative impact on the risk posture. Repeating this approach at Earth is the next level of risk.

Each of these regimes requires a different manner of performance on the part of the ERV, and as a result it can be considered one spacecraft that has to have the capabilities of two or more spacecraft. Obviously, increased cost is a consequence of these additional capabilities. However, this functionality needs to be tested with overlapping failure scenarios, and the probability of missing something increases with the complexity of the system. Ultimately, what simplifies one flight element usually transfers that functionality onto another element. Hence, an ERV that never captures at Mars forces a MAV to escape Mars. Eliminating the rendezvous functionality between the MAV and the ERV transfers that functionality into an ERV carried within the MAV. In the end, the MSR architecture design decisions boil down to a shell game of shifting performance responsibilities between flight elements. Occasionally, a significant shift in vision can provide this so called free lunch, eliminating a significant portion of functionality in one element without an equal increase in the required functionality of another flight element. These shifts in vision can be considered to be the three major architecture scenarios developed prior to 2001 (MOR, DR, DSR), with the introduction of a fourth as a result of the study this summer (LPR).

The earliest studies of Mars Sample Return initiated in the early 70s concentrated on an approach roughly analogous to the Apollo lunar missions of the late 60s. After surface operations, the Mars Ascent Vehicle launched from the surface and released a target vehicle into orbit about Mars. The Earth Return Vehicle would locate and rendezvous with the target vehicle and the sample would be transferred between the vehicles. This scenario, called Mars Orbit Rendezvous remained relatively unchanged until the mid 90s. At that point, a significant modification to the MOR architecture was conceptualized, and brought to maturity. This modification was the incorporation of telecommunications technology which had progressed far enough to eliminate much of the functionality of the target vehicle. This target vehicle was essentially reduced to a structure with a simple power system and location beacon. The resultant reduction in mass on the MAV was considerable, and best of all the functionality was truly eliminated from the entire architecture.

Through the 80s as propulsion, and avionics hardware became smaller and lighter, the possibility of eliminating the rendezvous step from the mission architecture presented itself in the development of a 2nd mission architecture option. This Direct Return architecture effectively placed the ERV within the MAV, and allowed for a direct placement of the samples into the ERV while still on the surface of Mars. Although, this architecture did eliminate the rendezvous from the entire mission, it did so at the cost of introducing functionality onto the ERV to survive both entry and ascent environments. The MAV itself did not require additional functionality, however the size of the MAV did grow considerably. However, the prospect of eliminating rendezvous from the architecture was and remains appealing, and as a result, Direct Return continues to be a contender in any architecture study. As in-situ propellant technology continues to mature, Direct Return will be the largest beneficiary of these advances.

As studies continued through the 90s, sensitivity studies indicated that the mass of the overall flight system was most sensitive to ERV delta velocity magnitude. The aeroshell of the Lander/MAV assembly can be thought of as a relatively high Isp propulsion system, making the assembly insensitive to MAV mass modifications. Additionally, the mass of the MAV was the lightest flight element of the architecture. By increasing to the MAV delta V to enable escape from Mars rather than simply going into orbit meant taking the impulse magnitude from 4300 m/s up to 6000 m/s. The effect of this on the MAV design, and propagating through the Lander was smaller than the impact of capturing and escaping the much heavier ERV. Taking this philosophy to the extreme produced the realization that the rendezvous does not have to be performed within the Mars gravity field, but can instead be performed in Heliocentric orbit. Ultimately, this architecture became known as Deep Space Rendezvous, and was the third known general architecture option.

Given these three general concepts as to where to perform the rendezvous, either on the surface of Mars, in Mars orbit, or on the heliocentric cruise leg, the next level of understanding for the architecture evolution was to create a design space of flight element interaction. Within this design space, each architecture candidate could be evaluated against science requirements to determine if it was able to satisfy them. This approach, generally considered a "follow the sample" philosophy encapsulates the entire mission architecture design trade space.

## 5. CANDIDATE ARCHITECTURES

The end-to-end trade space for a Mars sample return mission is shown in Figure 5-1. The regime includes the flight elements discussed in Section 3 along with implementation considerations such as operations, planetary protection, and system development, integration and test.

Through a systematic trade study process, the candidate architectures for a Mars Sample Return Mission listed in Figure 5-2 were identified. The eight configurations listed are classes of mission architectures, with each configuration containing several implementation nuances. For example, each configuration contains a MAV on either a rover or lander. However, the MAV can be either 1,2 or 3 stages; solid, liquid, or hybrid propellant; and incorporate guided or unguided navigation off the surface of Mars. Each of these approaches to returning a sample to Earth is feasible, however, there are significant levels of mission risk, technology requirements, and operational flexibilities associated with them.

Given this trade space, and the science requirements, a few options can be eliminated from further consideration. The requirement to drill 2 meters deep seemed to negate the benefit of carrying the drill on the rover. In the end, a rover that is drilling is not roving. Hence, the first line of the trade space, carry everything on a big rover, was eliminated from the trade space. This was a function that seemed more reasonable to place on the stationary landed platform. This does levy a new requirement on the rover that any excursion be a two-way trip, however, this was deemed an acceptable compromise.

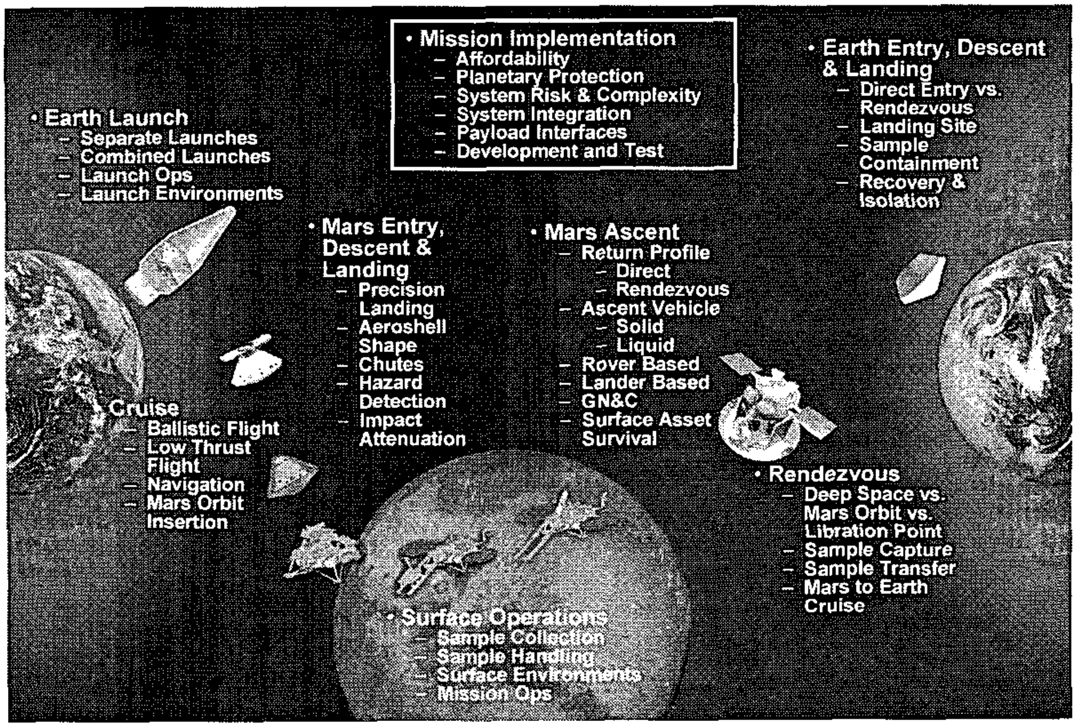


Figure 5-1 – MSR Architecture Design Phases

| Architecture Configuration | Comments |
|---|---|
| **Rover/MAV/ERV/SRC/Vault** | **Direct Return launched from Rover** |
| **Rover ←→ Lander/MAV/ERV/SRC/Vault** | **Direct Return on Lander** |
| **Rover ←→ Lander/MAV/ERV →SRC/Vault** | **Direct Return on Lander, Shuttle Rendezvous** |
| **Rover/MAV → ERV/SRC/Vault** | **Roving MAV, rendezvous** |
| **Rover ←→ Lander/MAV → ERV/SRC/Vault** | **Fixed MAV, Rendezvous** |
| **Rover ←→ Lander/MAV → ERV →SRC/Vault** | **Fixed MAV, Rendezvous, Shuttle** |
| **Lander/Rover → Lander/MAV → ERV/SRC/Vault** | **Sample Cache, Rendezvous** |
| **Lander/Rover → Lander/MAV → ERV →SRC/Vault** | **Sample Cache, Rendezvous, Shuttle** |

Figure 5-2 – Top-Level MSR Candidate Architectures

Given planetary protection requirements, it was decided that the opportunity to break the chain in a clean environment was also beneficial, although not given as an explicit requirement. Approaches to Direct Return that deliver a clean ERV into orbit from the MAV have been developed, however, the initial cleanliness of the ERV would need to be inferred assuming all protective barriers worked properly while on the surface of Mars and during ascent. For every rendezvous event, one can postulate a contaminate transferring from one element to another. However, the cleanliness of Direct Return options includes all the uncertainties of the rendezvous options, plus the additional uncertainty associated with the performance of protective barriers during the ascent. Hence, for this reason, Direct Return options that carried the EEV within the MAV were also eliminated from further consideration.

Direct Return architectures that deliver the samples into Earth orbit and uses the Space Shuttle for the EEV functions were also considered. Although this was viewed as a manner with which to break the chain, is was also noted that the samples are already within the Earth's biosphere. Uncontrolled particles that may have transferred from the exterior of the MAV onto the ERV during its release could also transfer from the ERV onto the exterior of the Shuttle. In the end, the absence of hard statistics as to the probability of contaminating the exterior of the shuttle did not deem the deletion of this option from the trade space at this phase of the study. All other lines of this trade space remained viable from the standpoint of science requirements and conservative planetary protection.

At this point in the study process, reduction of the trade space based upon specific architectures was initiated. Notice that the two rendezvous options have no discriminator within the high level description as shown. However, as one begins to place science requirements onto a specific rendezvous location, decisions can be made which eliminate some of the trade options. The desire to drill 2 meters, and to rove 1 km introduced a derived requirement for a minimum time allocated for surface operations. DSR architectures that launch a MAV and an ERV on the same opportunity do not easily accommodate long duration surface stays. Additionally, being able to launch the MAV at any time during the long surface stay is a beneficial risk mitigation option that was cumbersome to include into a DSR scenario. Hence, all DSR mission architectures that require the launch a MAV and an ERV together were eliminated from the trade space. Had the science requirements been compatible with a rapid grab sample acquisition technique, DSR would not have been eliminated.

A DSR mission architecture that launched a MAV on one opportunity, and ERV 3 years later remained attractive for a number of risk mitigation reasons. In this approach, the Lander/MAV flight element is launched to Mars in the first opportunity. After the surface mission has completed, the MAV places the samples directly onto a hyperbolic transfer that comes close to, but never crosses the orbit of Earth. Earth bound tracking of the OS will allow for accurate ephemeris reconstruction of the vehicle as it approaches Earth. As the OS flies through perihelion, about 3 years after launch from Earth and about 1 year after launch from Mars, the ERV is launched. The ERV acquires the sample and returns to Earth about 3 years after its launch. This architecture gives the dramatic reduction in ERV mass and complexity that is a hallmark of DSR architectures while preserving the operational flexibility of allowing a wide range of launch dates for the MAV.

During the evaluation of MOR architectures, the requirement to place the ERV into a low Mars orbit led to the comparison of four implementation approaches. The first, and most straightforward was an all-chemical propulsion system that takes the ERV from hyperbolic to low orbit, and then back again. This system is the most familiar, and could be considered the lowest risk from a technology development standpoint. It simply places a large injected mass requirement upon the launch vehicle. It requires the ERV to survive two flight regimes, deep space, and low orbit, but otherwise is fairly straightforward.

The second MOR approach, a propulsive capture using a low thrust electric propulsion system, and subsequent deorbit through a low thrust spiral trajectory was considered, and deemed the next logical level of risk from the standpoint of technical maturity and mission operations complexity. This technology has been demonstrated in a deep space environment, and it is a logical extrapolation to scale up the application to a Mars capture, deorbit, reorbit, and escape scenario.

The third MOR approach, a propulsive capture into a highly elliptical orbit, and the subsequent deorbit using aerobraking was also considered. This approach has been successfully demonstrated on Magellan, MGS and Odyssey and is an efficient method to deliver payloads into low Mars orbit. Unfortunately, it does nothing to assist in the Mars orbit escape phase of the mission. Additionally, previous Mars missions required vehicles to expended the large majority of their propellant in capturing into orbit at Mars. In the case of Mars sample return, the propulsion required to return to Earth would still be contained within the vehicle and its ballistic coefficient suffers. To accommodate reasonable aerobrake durations requires the inclusion of additional spacecraft surface area to solely to maximize the efficiency of the process. Finally, the consequence of interacting with the Martian atmosphere levies an additional flight regime upon the vehicle and thereby places an additional set of performance requirements on the vehicle. The uncertainty in Mars atmospheric modeling requires a great deal of flexibility in the mission timeline given a relatively fixed departure date. Hence, although this technology has been demonstrated at Mars and as a result is probably considered more mature than low thrust propulsion, the increased risk of atmospheric interaction and the inability to contribute directly to increasing the efficiency of the return flight caused it to be ranked third in order of merit to the mission.

The final MOR approach, aerocapture consists primarily of capturing directly to the final Mars orbit using a single pass through the atmosphere. The high heating involved in the aeropass requires the inclusion of a heatshield to protect the ERV. This heatshield can be very similar to the heatshields used to protect landers during their entry phases. Differences in lander thermal protection requirements are derived from energy management performance requirements for the atmospheric interaction to generate the desired velocity reduction. Hence, a derived requirement to include a moderate amount of lift into the ERV heatshield and the ability to guide this vehicle through the atmosphere to correct for uncertainties in atmospheric modeling must be included. Although neither of these requirements are great leaps in technology, neither have been demonstrated in the Martian environment. Coupled with the fact that this technology does not directly assist in escaping from Mars orbit to return to Earth, aerocapture was ranked fourth in value to the Mars Sample Return mission. Ultimately, the MOR trade space was reduced to two options for further consideration, an all-chemical MOR, and an all-electric MOR.

As the DSR and MOR profiles were compared, the benefits and drawbacks of each approach caused a reconsideration of the location of the sample rendezvous. The advantage of the DSR is the dramatic reduction in ERV mass and complexity through the elimination of the capture and escape burns, and the elimination of all flight environments except for cruise. The disadvantage of most DSR profiles is the short period of time the ERV is in the neighborhood of Mars and therefore its inability to recover from off nominal MAV launch dates. MOR has exactly the opposite set of pros and cons. Large deltaV expenditures upon the ERV are compensated for by the operational flexibility of having the ERV stay at Mars. It became obvious that a relocation of the rendezvous placement may be a reasonable compromise between the two extremes of MOR and DSR. Placing the ERV at the L1 point has a deltaV reduction benefit that reduces the mass of the ERV. The flight regime of the L1 point is simpler than cruise, with essentially fixed locations for the planet and the sun. The vehicle does not need to accommodate occultations or atmospheric interactions. However, since the L1 point is fixed relative to Mars, the profile is flexible relative to off nominal MAV launch dates by keeping the ERV in the neighborhood for long periods of time. Capturing at the L1 point can be accomplished with chemical or electric propulsion, although ultimately the chemical propulsion approach provides the lowest risk posture from a technology readiness viewpoint. Hence, for the first time, a compromise position between MOR and DSR appears to have been created that eliminates functionality on the ERV (cruise similar flight regime), reduces the impulse magnitude levied upon the largest single flight element, and preserves the operational flexibility for off nominal surface mission evolution. As a result Libration Point Rendezvous (LPR) was considered a reasonable MSR mission architecture with characteristics that are separate and distinct from either MOR or DSR.

# 6. MOR AND LPR MISSION DESIGNS

The LPR mission, shown in Figure 6-1, begins with the single launch of all flight elements on a Delta IV 4050H launch vehicle. After a direct entry to the surface of Mars, the Lander deploys the rover to collect samples of rocks and surface material from multiple sites, and additional samples are collected with a drill and manipulator arm mounted to the Lander. The samples are then processed on the Lander workbench, loaded into the sample canister, cleaned and aseptically transferred into the MAV. The MAV is launched towards the Mars-Sun libration point (L1). As it arrives at this point, the final stage of the MAV fires to decelerate and releases the Sample Canister Assembly (SCA), which drifts through the L1 region. The ERV is prepositioned at the L1 region and tracks the MAV's ascent where it performs a rendezvous with and capture of the SCA. The sample canister is transferred into the EEV vault and the ERV returns to Earth. Upon arrival at Earth, the EEV performs a targeting maneuver, spins up, and releases the EEV from the ERV. The EEV passively enters the Earth's atmosphere, descending to the Earth's surface. The EEV performs a deflection maneuver to avoid entering the Earth's atmosphere.

The nominal aim point the MAV is biased away from the L1 Point, in the opposite direction of the motion of Mars in the L1 centered reference frame as shown in Figure 6-2. The magnitude of the bias is a function of the anticipated uncorrected Stage 1 and 2 impulse variations. Low performing motors will deliver the third stage onto a somewhat slower trajectory up to L1, and as a result will spend more time being perturbed towards Mars (East). Rather than randomize the approach vector, it was determined that an OS that spends time approaching the ERV from a preferential direction would be advantageous from the standpoint of acquisition and tracking. The OS brakes at a point perpendicular to the L1 – Sun line, and begins to drift towards the ERV, passing through the L1 space. At that time, the ERV matches the velocity and recovers the OS. After sample transfer, the ERV performs a propulsive maneuver to return to L1 and wait for the appropriate time to return to Mars and perform a TEI burn.
Variations to the performance of the MAV Stage 1 and 2 motors will place the stage 3 assembly onto faster or slower trajectories to L1. These dispersions are corrected by modifying the behavior of the fixed attitude stage 3 burn, primarily the timing and magnitude of the delivered impulse. Off nominal performance of the Stage 1 motor can be corrected by adjusting the stage 2 motor ignition time.

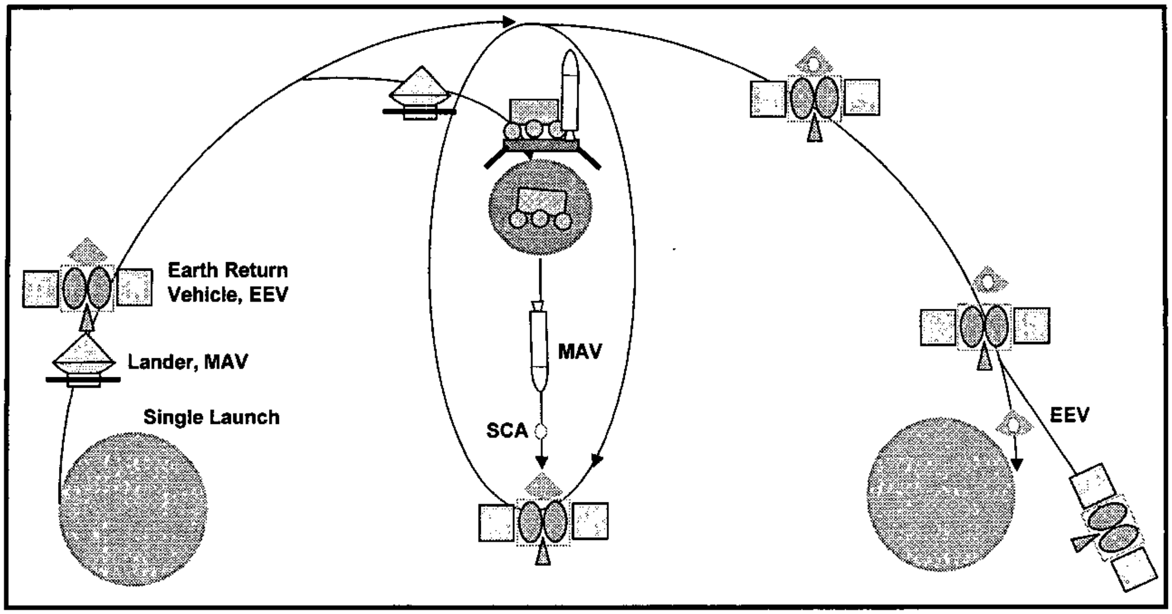


Figure 6-1 – MR Libration Point Rendezvous Architecture

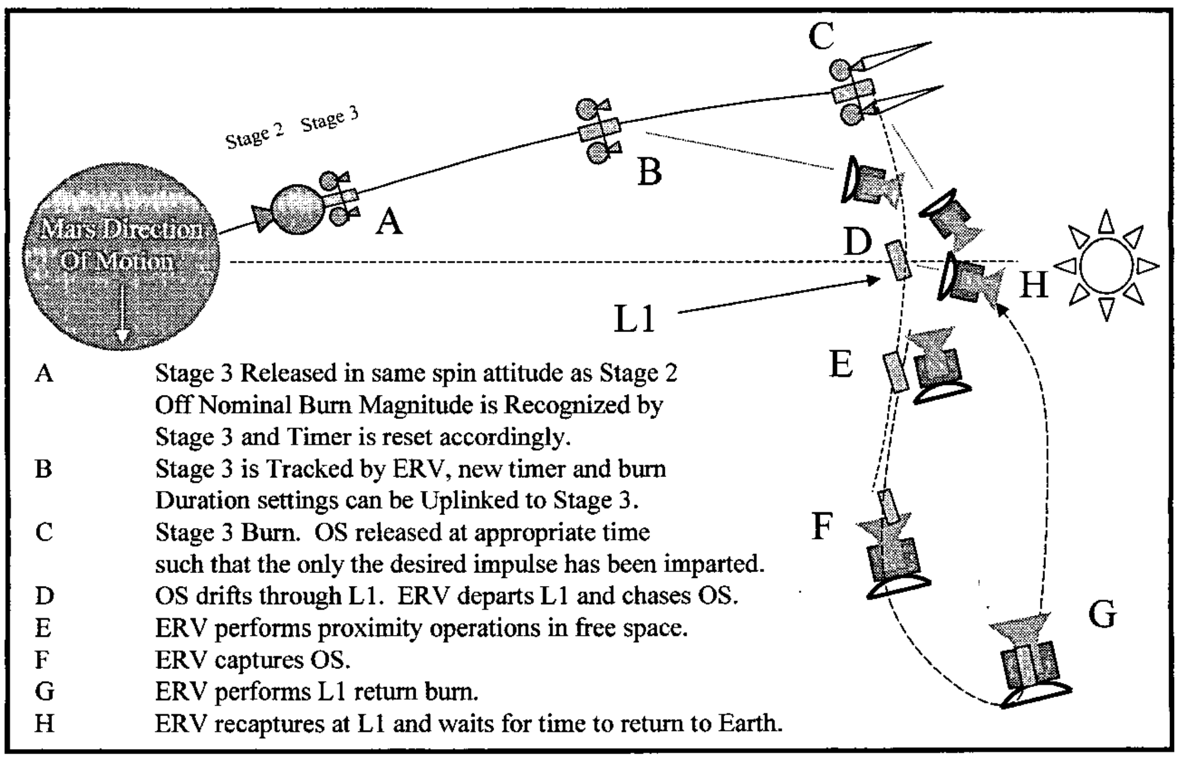


Figure 6-2 – MAV Trajectory in the LPR Architecture

North Pole views of the Libration Point Rendezvous nominal trajectory for the ERV and the MAV/OS are shown in Figure 6-3. The left view is the libration point centered reference frame and the right view is the Mars centered frame. This MSR architecture incorporates the following observations:

1) Fast Capture of ERV into L1 space is needed for dual manifest launches.
2) L1 Free Return trajectories are highly sensitive to small injection errors.
3) A robust TCM capability for the OS during the transit to L1 is mass prohibitive.
4) MAV injection errors are easily managed with faster ascent trajectories.
5) The price of this error management capability is the introduction of a braking stage.
6) The geometry of the MAV ascent is compatible with an unguided braking stage.
7) The braking stage must have an ability to adjust the magnitude of the OS impulse.
8) The geometry of the MAV ascent may be compatible with a simplified TCM capability.
9) Biasing the target point west of L1 produces OS trajectories that move to L1.
10) Appropriate selection of the bias can manage the anticipated dispersions.

The MOR mission, shown in Figure 6-4, begins with dual launches of the flight elements. The ERV and EEV are launched on a Delta IV 4050H vehicle, while the Lander (with MAV and Rover) is launched on a Delta IV 4450 vehicle. After a direct entry to the surface of Mars, the Lander deploys the rover to collect samples of rocks and surface material from multiple sites, and additional samples are collected with a drill and manipulator arm mounted to the Lander. The samples are then processed on the Lander workbench, loaded into the sample canister, cleaned and aseptically transferred into the MAV. The MAV is launched into low Mars orbit and releases the SCA, which is then rendezvoused with and captured by the ERV. The sample canister is then transferred into the EEV vault and returned to Earth. Upon arrival at Earth, the EEV performs a targeting maneuver, spins up, and releases the EEV from the ERV. The EEV passively enters the Earth's atmosphere, descending to the Earth's surface. The EEV performs a deflection maneuver to avoid entering the Earth's atmosphere.

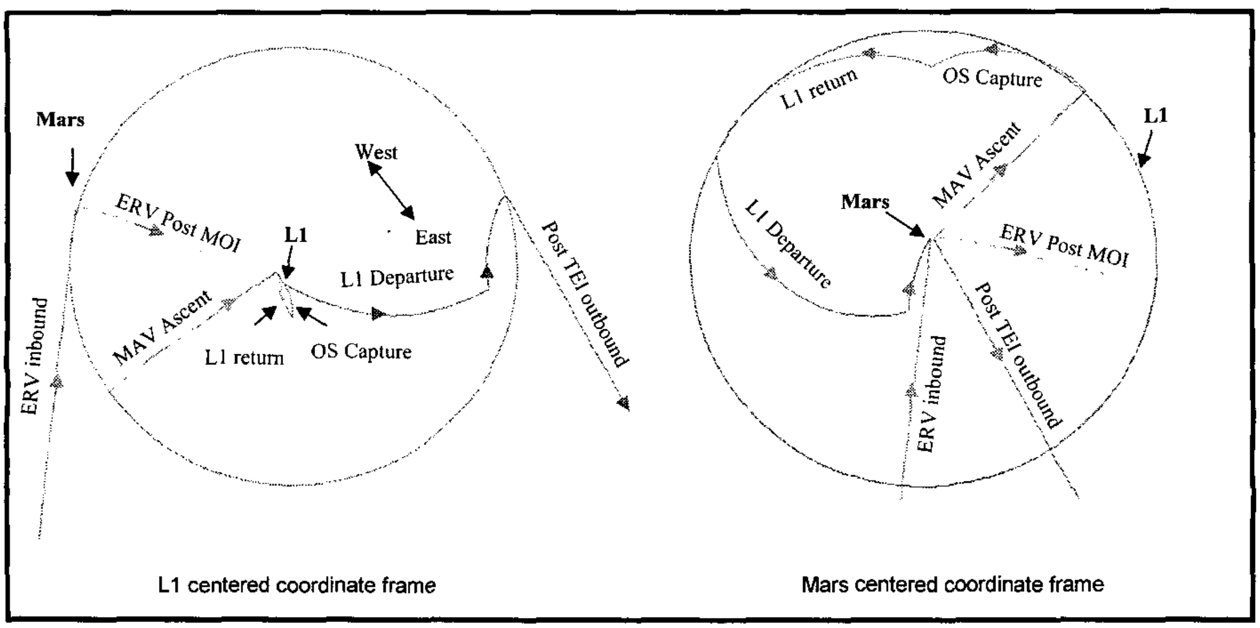


Figure 6-3 – LPR Nominal ERV and MAV/OS Trajectory

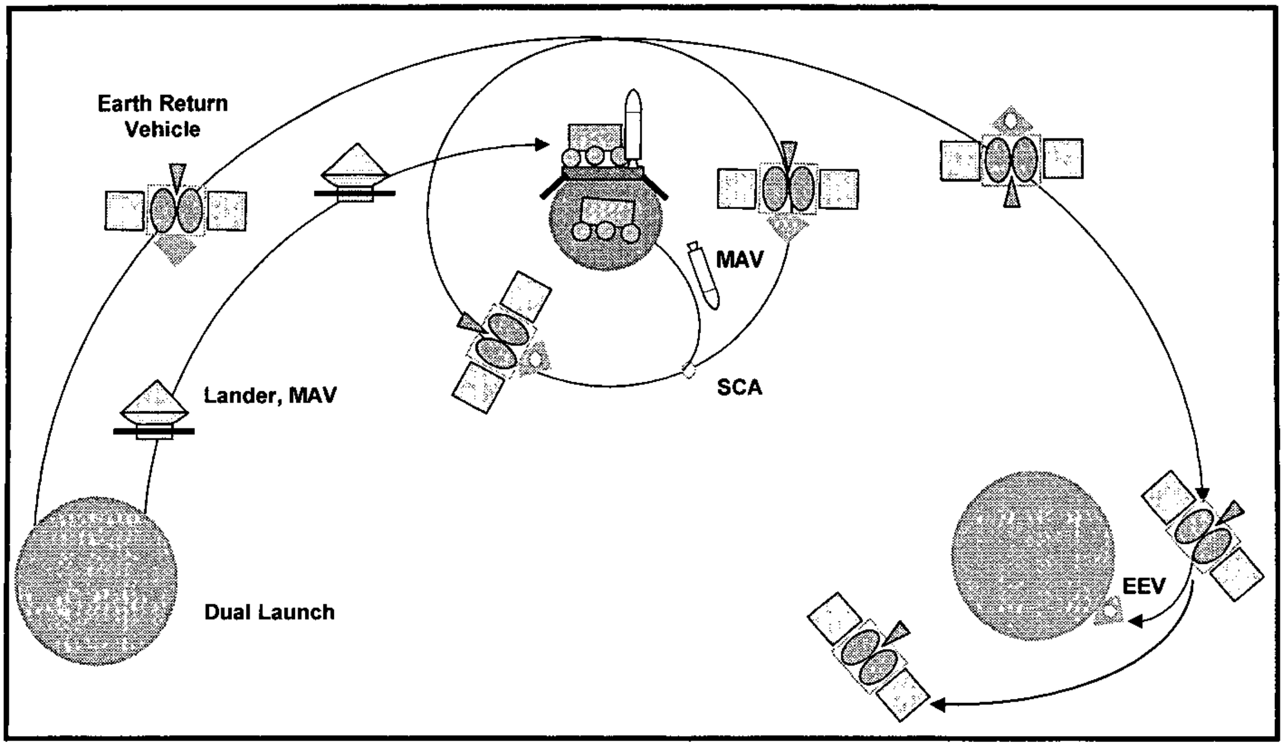


Figure 6-4 – MSR Mars Orbit Rendezvous Architecture

The heliocentric north view of the all-chemical MOR mission, shown in Figure 6-5, highlights the operational simplicity of the mission. Out bound cruise for both the ERV and the Lander/MAV are ballistic transfers. The Lander is targeted for arrival at Mars earlier than the ERV to maximize the amount of time spent on the surface. This introduces an interesting complexity to the mission in that an early launch of the MAV could happen without an ERV in the vicinity. Hence, the state of the OS may not be known prior to ERV arrival and the ERV may be forced to search for the OS. Strategies for eliminating this uncertainty were developed using other assets at Mars. Capture of the ERV into Mars orbit was most efficiently done with a separate solid propulsion stage that was jettisoned after Mars orbit insertion. This reduces the mass of the ERV without a significant reduction in efficiency. The circular orbit that the ERV captures into is able to accommodate the proper inclination and right ascension requirements needed to transition from sample capture to departure node alignment. Planetary protection requirements to place a clean sample into orbit are maintained in both MOR and LPR scenarios. The ERV return to Earth is ballistic, with the samples returned about 3 years after launch.

## 7. MSR Architecture Summary

Through the process described in this paper, architectures for conducting a Mars Sample Return mission were defined and evaluated. Following a systematic design and evaluation process, the study concluded with two promising MSR architectures which merit further study. Key findings of Libration Point Rendezvous and Mars Orbit Rendezvous architectures are summarized in Figures 7-1 and 7-2.

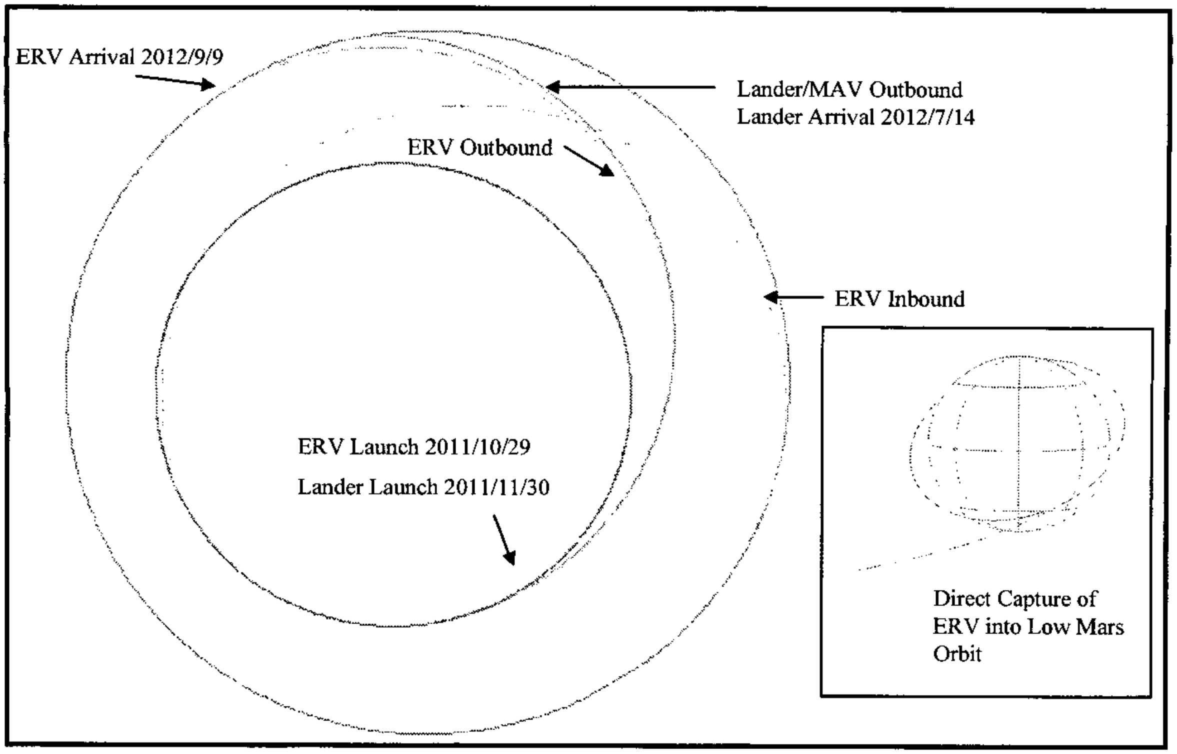


Figure 6-5 – MOR Nominal ERV and Lander/MAV Trajectory

**Libration Point Rendezvous Observations**

**ERV Could be a Stretched Version of Mars Odyssey**
**MAV/Rover/Lander Would be a New Set of Flight Elements**
**Single Launch on Delta IV 4050H**
**Allows for 90 Sol Landed Mission**
**Allows for 7 months ERV Orbit Ops at Libration Point**
**Allows for 3 months Rendezvous Ops After SCA passage Through L1 Plane**
**No Opportunity for Long Range Sample (2 x 10 km Rover difficult in 90 sols)**
**MAV Ascent Accuracy and Dispersion Control is Non-Critical for This Scenario**
**Effect of MAV Dispersions on ERV DV budget**

| Pros | Cons |
|---|---|
| Low DV ERV | MAV 3rd Stage Ads Mass/Complexity |
| MAV Launch Accuracy Non-Critical | Long Range Tracking of SCA ups Mass |
| EEV System Very Robust | ERV at L1 if MAV Fails |
| Constant Visibility of SCA from ERV | Weak Stability of L1 needs additional DV |
| Low Possibility of ERV Entry at Mars or Earth | Longevity of SCA at L1 if ERV fails |
| Can Launch on a Single LV (Delta IV) | LPR Rendezvous Still Conceptual |
| ERV can be Stretched Version of Odyssey | |

Figure 7-1 – MSR LPR Architecture Findings

| Mars Orbit Rendezvous Observations | |
|---|---|
| MAV/Rover/Lander Launch on Delta IV 4450 | |
| ERV Launch Possible on Delta IV 4050H | |
| Opportunity for 1 km Surface Mobility Science | |
| Allows for 90 Sol Landed Mission. | |
| Allows for 3 months Rendezvous ops after SCA injection | |
| No Opportunity for Long Range Sample (2 x 10 km Rover difficult in 90 sols) | |
| MAV Ascent Accuracy and Dispersion Control is Critical but understood | |
| **Pros** | **Cons** |
| ERV in Mars Orbit if MAV fails | Longevity of SCA in Mars orbit if ERV fails |
| EEV System Very Robust | Tight MAV Launch Accuracy |
| MOR Rendezvous Well Understood | Multiple Design Environments for ERV |
| Stability of SCA Final Orbit if Good Injection | Rely on Orbital Assets for OS Tracking |
| Low Possibility of ERV Entry at Mars or Earth | Requires two LV (both Delta IV) |

Figure 7-2 – MSR MOR Architecture Findings