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A Mars Sample Return Strategy

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Intermediate Rendezvous: A Mars Sample Return Strategy

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This paper describes the issues and challenges related to the design of the rendezvous between the Earth Return Vehicle (ERV) and the Orbiting Sample (OS) for the Mars Sample Return (MSR) mission. In particular, attention will be focused on the strategy for "optimizing" the intermediate segment of the rendezvous process, during which there are a great number of variables that must be considered and well understood.

Intermediate rendezvous refers to the matching of the ERV orbit to that of the OS upon completion of the ERV aerobraking phase. This activity includes having the ERV enter a phasing orbit to align the nodes, and then propulsively matching the orbital elements of the OS (aside from the true anomaly which is nearly matched). However, the intermediate rendezvous process itself cannot be planned independently. This piece of the mission needs to be thoughtfully integrated into the MSR mission architecture, where its implementation will ripple through the design and affect everything from Mars Orbit Insertion (MOI) to Trans-Earth Injection (TEI), to even landed elements such as the Mars Ascent Vehicle (MAV). Therefore, several issues must be considered when constructing a strategy for intermediate rendezvous, including: MAV launch timing (determines OS node) and launch window considerations, the size of the orbit the MAV delivers the OS to, the associated injection accuracy of the MAV, orbital inclination to be targeted with respect to the assumed landing site latitude, the trade between the time available and the ΔV required for the rendezvous process, and the geometrical and energy variations (e.g. arrival and departure hyperbolic excess velocity vectors) between various MSR mission launch opportunities, etc.

Nomenclature

ω	=	Argument of Periapsis
C3	=	Injection Energy (V_∞^2), km^2/s^2
DAP	=	Declination of the Arrival Asymptote
DLA	=	Declination of the Launch Asymptote
ΔV	=	Delta-V
ERV	=	Earth Return Vehicle
GLOM	=	Gross Lift Off Mass
ISP	=	Specific Impulse
KM	=	Kilometers

Ω = Longitude of the Ascending Node
MAV = Mars Ascent Vehicle
MOI = Mars Orbit Insertion
MSR = Mars Sample Return
OS = Orbiting Sample
RAN = Rendezvous and Autonomous Navigation
RLA = Right Ascension of the Launch Asymptote
TEI = Trans-Earth Injection
V_∞ = Hyperbolic Excess Velocity, km/s

Introduction

The Mars Sample Return Project represents an effort to retrieve a sample of Martian rock, regolith, and atmosphere and return it safely to Earth. Currently, the state of the project is not a firm one, and a number of trades are still open for consideration to either reduce cost and/or increase the attractiveness of the overall mission. Some of these trades could include: one vs. two Landers, the number of launch opportunities utilized, the order in which the space elements arrive, or even designing the orbiting spacecraft to double as a communications satellite to support other missions.

In particular, a number of these trade studies stem from the rendezvous process that occurs between the Earth Return Vehicle and the Orbiting Sample. The need for this rendezvous is derived from the inability to land a sufficient amount of mass (mostly in the form of propellant) at Mars to perform Trans-Earth Injection directly from the surface. In solving this dilemma, the sample is launched into a low orbit by the Mars Ascent Vehicle which is carried to the surface by the Lander. From this point, it is the orbiting ERV that is tasked with the responsibility of retrieving and transporting the sample back to Earth.

Since rendezvous is so vital to both mission success and preserving margin, it has become a keystone of the project's focus. This strategy must be thoughtfully integrated into the design of the mission and should yield the most favorable combination of time and ΔV required for the chosen architecture. This multi-dimensional problem, coupled with other mission architecture trades, lays the framework for a volatile environment for analysis. This paper addresses this problem from a mission design perspective and shows the dynamic effects it instills across the flight elements in the MSR system.

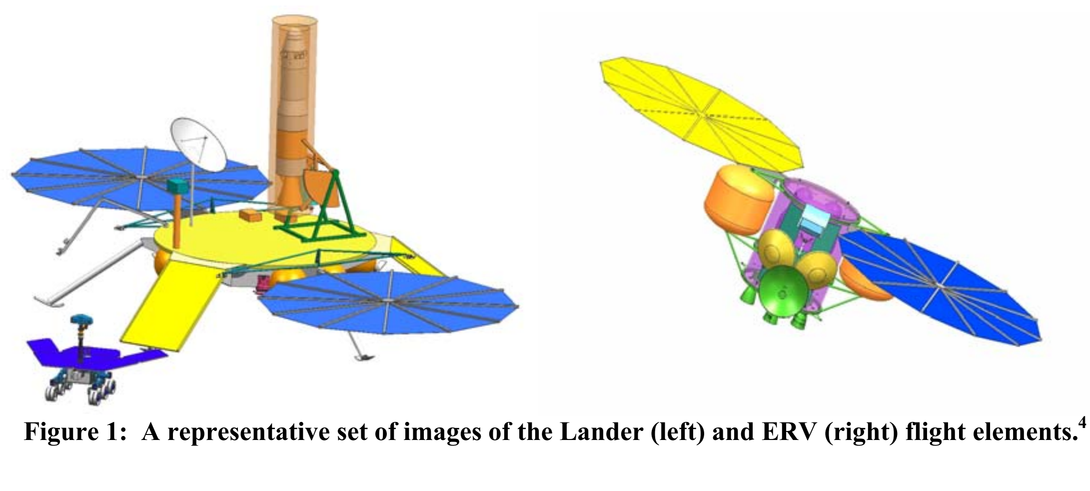


Figure 1: A representative set of images of the Lander (left) and ERV (right) flight elements.[4]

The Rendezvous Strategy

While rendezvous can often be thought of as strictly docking one spacecraft to another, in the case of Mars Sample Return it has become difficult to decouple any of the events occuring between Mars Orbit Insertion and

Trans-Earth Injection. Therefore, it is more useful to instead to think of this entire series of events as the Mars arrival and departure "dance". This term has been deemed suitable in light of the precise timing and positioning that is required throughout the spacecraft's stay at Mars.

Mars Orbit Insertion

MOI marks the first of a series of events included in "the dance", and is the source of immediate bounds placed on the rendezvous problem. With the demand of landing site access stretching across all latitudes between 45S to 45N, the ERV is forced to accommodate this by inserting into an orbital inclination of no less than 45 degrees. This is essential, as launching the MAV into an inclination lower than its landed latitude yields a huge performance hit. In fact, the GLOM will increase 2 orders of magnitude faster for decreasing the target orbit inclination over the landed latitude as compared to increasing it[5], which is primarily due to the fact that such a maneuver requires a plane change rather than simply launching to a non-zero azimuth. By inserting the ERV into an inclination greater than the maximum Lander latitude, the MAV will be able to target the ERV's orbit inclination without performing any form of plane change. However, it is still pertinent to disallow the inclination from becoming any larger than necessary to maximize the rate of nodal precession (which minimizes the time required for the ERV and OS to match nodes) prevent an increase the Mars Ascent Vehicle performance. The nature of these performance hits can be observed in the Figures 2 and 3 below.

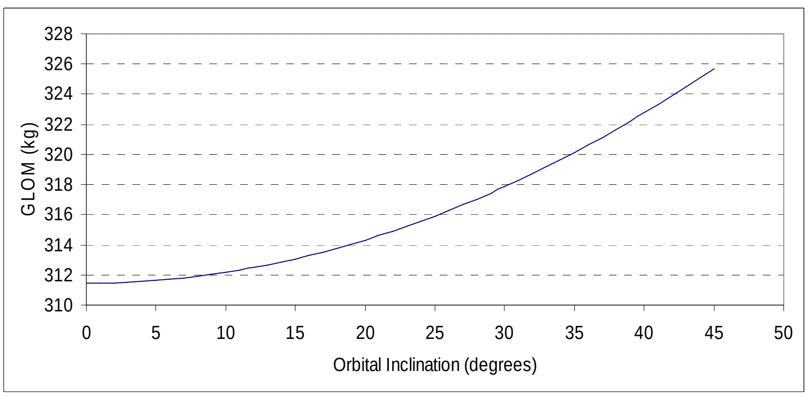


Figure 2: Gross lift of mass is shown here as a function of the inclination of the orbit it is firing to. The higher the inclination the MAV is required to send the OS to, the less it is able to take advantage of the rotation of the planet. This necessitates the expulsion of additional ΔV and thus requires larger amounts of propellant.

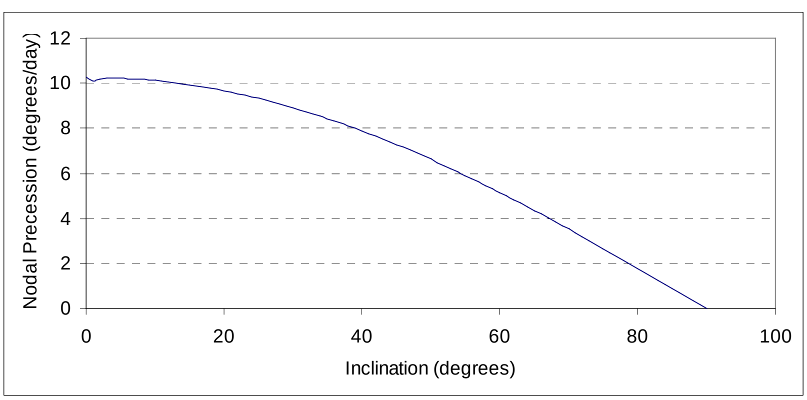


Figure 3: Westward Nodal Precession shown as a function of inclination. The orbit shown in flux here has a semi-major axis of approximately 3800 km.

Still, one additional caveat remains to be discussed. That is, only inclinations greater than the DAP at ERV arrival and the DLA at ERV departure are viable, as any lower value requires an out-of-plane burn and necessitates a prohibitive amount of propellant during MOI or TEI. Therefore, a particular opportunity with a large declination in the incoming or outgoing asymptote would further hinder the performance of the rendezvous strategy by requiring a comparatively larger inclination rendezvous orbit, resulting in additional time, ΔV and/or MAV performance. Fortunately, the greatest DLA or DAP in the 2016 and 2018 opportunities is much less than 45 degrees and does not yield any significant rendezvous performance reductions.

At this point, essentially only two insertion planes remain available at Mars. These insertion planes include the North and South orbit insertions that yield a final orbital inclination of 45 degrees. By narrowing the insertion planes down to two, the viable options for Ω are thus limited to the same value, and this highly constrains the initialization of the arrival and departure dance at Mars.

Aerobraking

Once the MOI burn is executed, the next major rendezvous event completed by the ERV is aerobraking, which is initiated with a maneuver to lower the periapsis to 100 km[1]. With each successive pass through Mars's upper atmosphere, the ERV's apoapsis is decreased due to the drag inflicted on the spacecraft, and the altitude profile then proceeds to decrease nearly linearly with time. This is illustrated in Figure 4 below. Such a process allows the ERV to insert into a much higher period orbit at MOI, thus saving ΔV (and propellent mass) in exchange for the time required to lower the orbit apoapsis to the desired altitude.

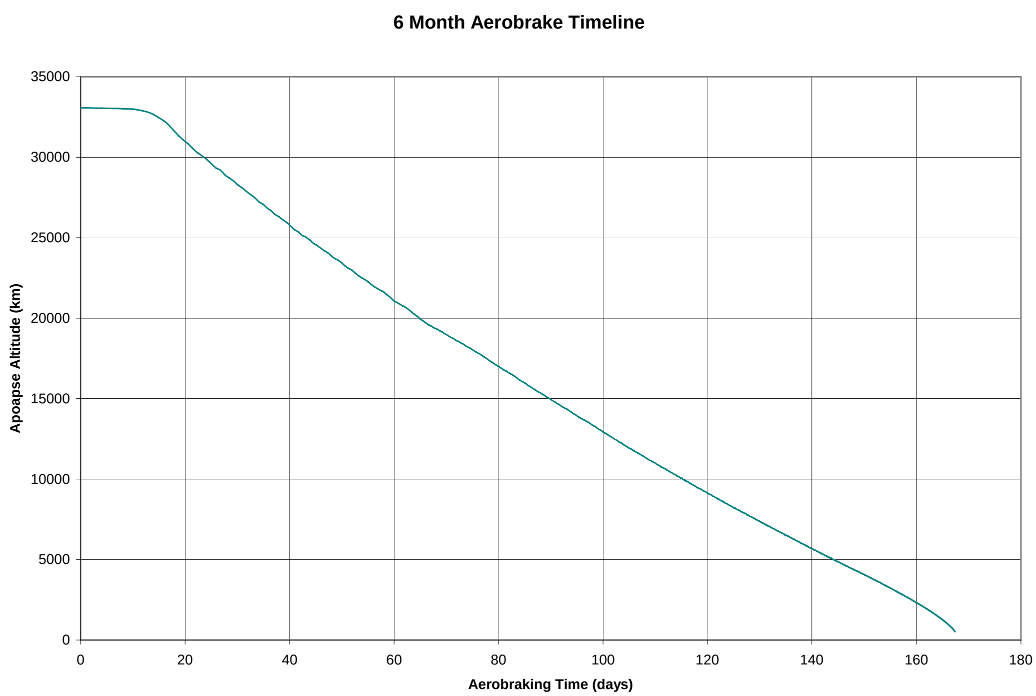


Figure 4: The aerobraking profile for the ERV.[4]

The benefits of using aerobraking reach beyond the ΔV it which is saves for MOI. That is, since the ERV is given the burden of rendezvousing with the OS, it can take this opportunity to save further ΔV by halting aerobraking and inserting itself into a nodal phasing orbit (shown in Figure 5). Then, not only is the ERV be able to save time and possibly ΔV while aligning its orbit plane with that of the OS, but it may also have the ability to utilize targeted drag passes as a means of matching not only orbit size, but other orbital elements as well. If the ERV is launched in an opportunity prior to the Landers, it may be most beneficial to first perform only a portion of the aerobraking process. This would allow the ERV to reside in a "parking" orbit that can be used for nodal phasing, and possibly other scientific or infrastructure (e.g. telecom relay) purposes while awaiting Lander arrival.

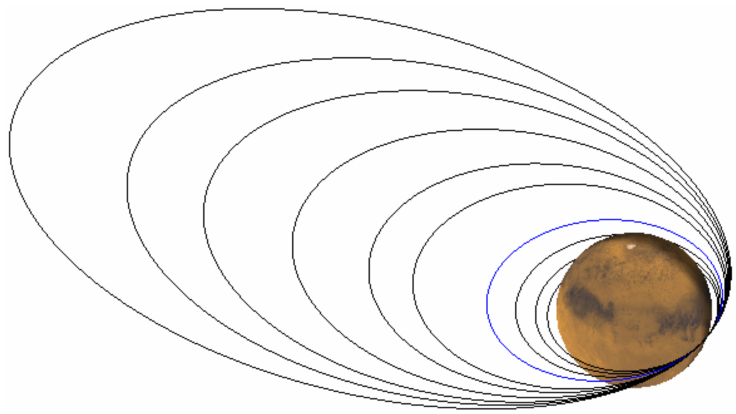
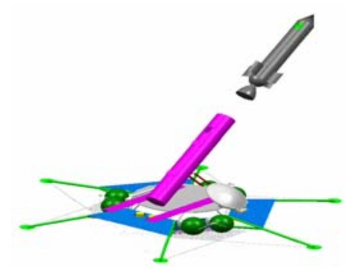


Figure 5: The aerobraking profile shown in Figure 4 is depicted here, where the blue orbit indicates the nodal phasing orbit that aerobraking would be temporarily halted in.

Launching the MAV

A large portion of the rendezvous strategy lies in choosing the orbit targeted by the MAV. After only 90 days on the surface, the Lander's mission is concluded, and the MAV proceeds to launch a sample canister into orbit about the planet. The OS itself is a 14-16 cm spherical canister containing approximately 0.5 kg of sample[2], and its ascent from the surface requires a great deal of attention for formulating a rendezvous strategy.

The current reference MAV design is based on the use of solid propellant[5] (due to mass and volume constraints), thus the MAV cannot precisely control the amount of ΔV it produces since solid motors are required to burn to completion. The MAV can, however, control the launch azimuth (target orbit inclination) and time of day which it launches (node location). The level of control desired, even in these elements, has a significant impact on the MAV design (e.g. propellent sizing). The current MAV design concepts are based on a preliminary requirement that the dispersions in orbit size be +/- 100 km in both the periapsis and the apoapsis[1]. Due to the uncertainties in the Lander's orientation and the direction of the second-stage burn, the dispersions in the orbit plane are currently assumed to be +/- 1 degree in the inclination, and +/- 3 degrees in the longitude of the ascending node[1]. As a result, these dispersions make it extremely difficult to predict and plan for any form of exact rendezvous or departure phasing.



MAV Launch Representation[4]

An additional constraint is that sufficient mass/performance should be allocated to the MAV in order to deliver the OS to an orbit in which it can survive at least 10 years. The purpose of this requirement is to ensure that any sample in Mars orbit might be retrieved at later Mars mission opportunities, particularly in the case where two OS's are placed in orbit, but only one is retrieved by the ERV during the first MSR mission. Figure 6 below shows that any circular orbit below 240 km will not meet the 10 year orbit lifetime requirement, and thus an orbit altitude of at least 350 km should be targeted to ensure that the dispersions do not result in failing to meet this constraint.

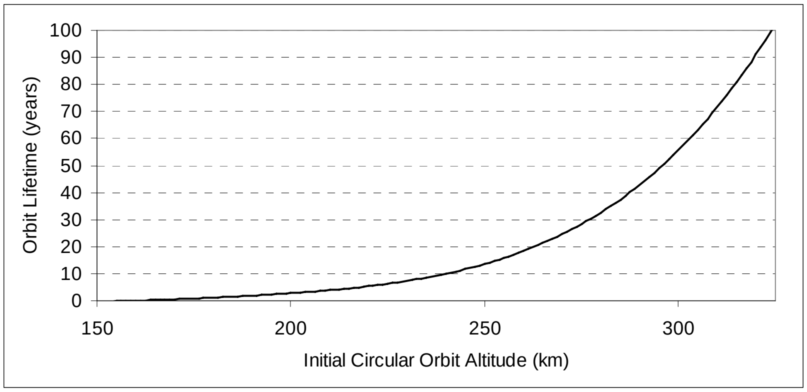


Figure 6: The orbit lifetime is highly a function of the mass and cross-sectional area of the spacecraft, along with its orbital altitude. Here, it is assumed that the total mass of the OS is 3.8 kg and is a perfect sphere, 16 cm in diameter

It would be reasonable to suggest that effort be placed in minimizing the 100 km dispersion error to allow the targeting of a smaller orbit. However, shrinking the orbit dispersions requires a hefty increase in the MAV mass by the addition of some propellent/system capability to the 2nd stage ACS system. Therefore, these negative effects of tightening dispersions outweigh the potential mass savings presented by launching to a lower orbital altitude.

Intermediate (and preliminary) rendezvous

After the ERV has inserted itself into a phasing orbit, it needs to locate the OS. The imaging sensors onboard the ERV allow for the primary means of OS detection. In addition to this, a back-up capability is under consideration in which the OS possesses a battery-powered beacon emitting a signal that can be recognized by the Radio Direction Finder (RDF) on-board the ERV. The range for which both optical and radio detection is possible is approximately 3000 km[1], but detection can only be achieved if the OS is not occulted by the planet and is also in sunlight (for optical detection). Once the OS is located and tracked sufficiently long to well determine its orbit, this first phase of rendezvous is concluded. However, it should be noted that the range of detection capability seriously inhibits the rendezvous process in the form of time, and potentially ΔV. That is, the size of the ERV's phasing orbit needs to accommodate the detection of the OS and will therefore be restricted in its orbit size, which reduces the differential node rate which it can achieve. With the current optical detection capability, the largest nodal phasing orbit that can be chosen will be 250 km by 3000 km (3 hour period) altitude. The rate at which such an orbit regresses can be seen in Figure 7 below.

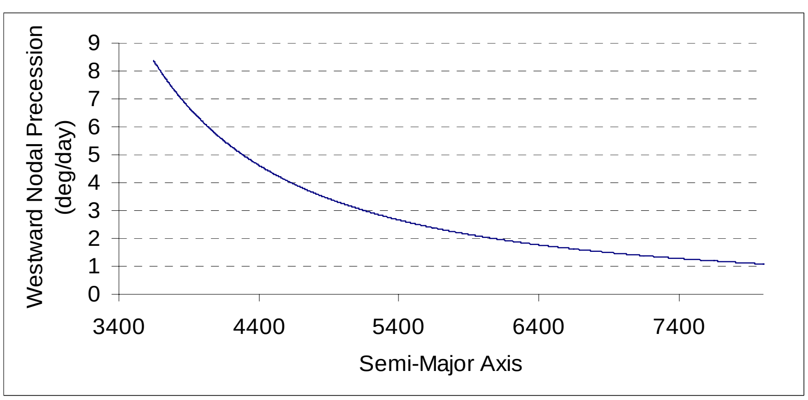


Figure 7: This shows the large affect that the semi-major axis can have on the nodal precession of the orbit. It is assumed here that the inclination is held constant at 45 degrees.

Once the OS is located, the ERV, in turn, begins matching the orbit and position of the OS. This phase is referred to as intermediate rendezvous (illustrated in Figure 8), and is concluded once the ERV has nearly matched the orbital elements of the OS and reduced the separation between the two spacecraft to 5-10km[3]. The first step in achieving this goal is to match the OS's inclination with an out-of-plane maneuver by the ERV, where each degree of inclination change translates to approximately 40 m/s of ΔV. However, the remaining elements cannot all be matched propulsively. For example, at the instant the OS orbit is detected, it is unlikely that the longitude of the ascending node of this orbit will match the ERV's, and it could be off by nearly 360 degrees. It would then require approximately 40 m/s for every degree of node change, and thus would be prohibitively large for any significant separation in Ω. Therefore, the ERV needs to be placed into a nodal phasing orbit to allow for the nodes to be aligned by the natural precession of the orbit planes driven by the oblateness of the planet. Since the orbits share nearly the same inclination at this point, the magnitude of the differential nodal precession rate between them is almost entirely a function of their difference in the semi-major axis. The magnitude of such nodal precession trends can then be determined from, once again, examining Figure 7.

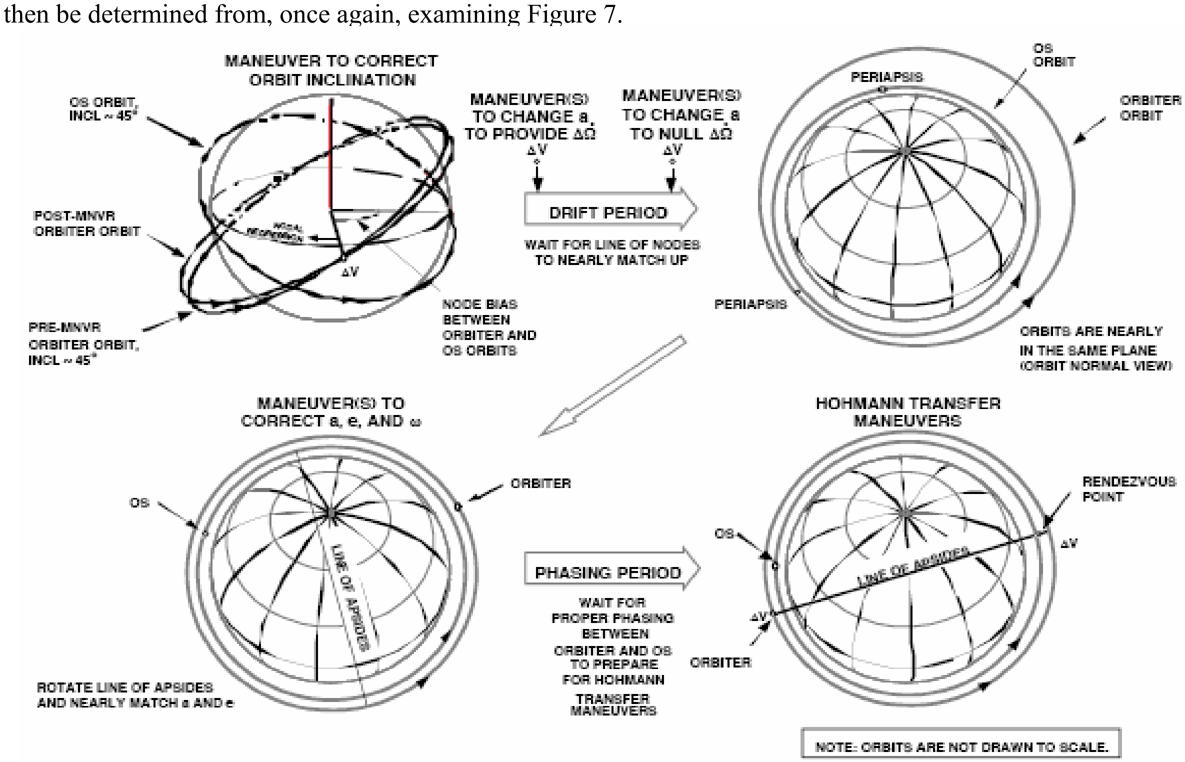
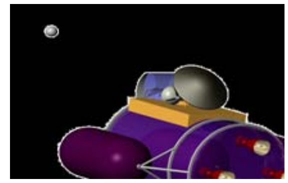


Figure 8: An illustration and explanation of the intermediate rendezvous process.[3]

In time, this differential nodal precession rate provides for nodal alignment between the two orbits. Still, even if the nodal separation is not large, this can be a very time consuming process. Nevertheless, once the nodes have been nearly matched, the ERV can then proceed to nearly match the remaining orbital elements with aerobraking and/or coplanar orbital maneuvers. Upon their completion, the ERV's orbit should have an inclination, argument of periapsis, longitude of ascending node, and eccentricity nearly identical to the OS's orbit while having a slightly lower semi-major axis to ensure that the ERV is approaching the mean anomaly of the OS with time. Also, the ERV should remain in a path below and behind the OS to mitigate any risk of collision between the two spacecraft. Finally, a near–hohmann transfer will be performed to place the ERV within the desirable 5-10 km range of the OS, however it is anticipated that the duration of these events, following nodal alignment, can require as much as 3 weeks to complete. Once within this range, intermediate rendezvous is said to be completed, and the terminal rendezvous process begins.

Terminal Rendezvous

The terminal rendezvous phase is responsible for the final capture of the OS and will be performed using a RAN capability currently under development. This approach is beneficial since the roundtrip communications time between Earth and Mars can be as much as 43 minutes, which can be problematic when attempting to capture the OS when operated from the ground. The ΔV allocation for this autonomous process will be 40 m/s. Upon capturing the OS, the ERV may then begin the departure phase in which it will align itself to a suitable departure orbit in time for TEI.



Terminal rendezvous representation[4]

Retrieving a second OS

If indeed an additional Lander has accompanied the first, and also successfully launched a sample into orbit, a decision must be made. Once the first OS is captured successfully, should the project risk the success that is nearly at hand to attempt a second rendezvous?

It is certain that this decision has several implications on both the overall rendezvous strategy, as well as the amount of propellant that is needed onboard the ERV and the time available between MOI and TEI. To support a second rendezvous, the bulk of alterations made to the mission design will need to accommodate tightened time constraints and additional maneuvers. The magnitude of such effects, however, will vary from one mission architecture to the next. In response to these difficulties, new constraints and requirements will need to be thoughtfully integrated into both the rendezvous and its contiguous components of the mission design.

First, the addition of a second landed payload may necessitate an increase in the performance (and thus mass) of the MAV since the system needs to be designed for the more stressful of the two landing sites (latitudes) in order to keep both MAV's identical. If the ERV is launched in an opportunity after the Landers, the landing sites will be known when the ERV is en route to Mars, and the inclination can be chosen accordingly. It is then most advantageous for the inclination of the ERV to be no larger than the greatest latitude for reasons described in the *MOI* discussion above. The worst case scenario, therefore, occurs when one landing site is at a latitude of 45 degrees. Then, even if the other landing site were to be at the equator, the MAV would have to launch at a high azimuth and thus incur performance degradation. It should be noted, however, that if the ERV is launched before the Landers, just as in Example Architecture 3 below, the same design is necessary, as the landing site are unknown and 45 degrees must be used to accommodate all landing site options.

An additional constraint which is greatly tightened by the addition of a second OS is the time available. Each unique mission architecture provides a different stay time than the others, where the less time made available for the entire rendezvous process inevitably requires a greater amount of ΔV. What is more, in the case of the second OS, the ERV cannot use aerobraking to establish a nodal phasing orbit for rendezvous with the second OS. Therefore, it has to use propulsive maneuvers to increase its semi-major axis to create the necessary differential nodal drift between the two spacecraft. As a result, the greater amount of time available allows for less ΔV. However, the ΔV can be further reduced by decreasing the worst case amount of nodal drift necessary. This can be done by targeting the second OS to a nodal value of $[2(\Delta\Omega_1) + 2(\Delta\Omega_2)]$, where $\Delta\Omega_1$ is the total nodal uncertainty in the first OS and $\Delta\Omega_2$ in the second. The magnitude of this uncertainty is determined by multiplying the number of days separating nodal phasing and MAV liftoff by the daily nodal uncertainty created by MAV dispersions.

Finally, even after the nodes have been matched between the two orbits, transfers analogous to the first rendezvous still remain, where aerobraking cannot be used to relieve any of this ΔV burden. It should be noted that every additional m/s of ΔV needed during rendezvous with the first OS alone increases the mass of the ERV by 3-4 kg, as the additional propellant required for these maneuvers must be carried by the spacecraft throughout all those preceding them. The effects of adding ΔV for a second rendezvous will be even more dramatic. Also, the additional structure needed to accommodate the capture and transport of the second OS could grow to be as much as ~500 kg.

Trans-Earth Injection

Whether it is after retrieving one sample or two, Trans-Earth Injection remains a crucial event in the arrival and departure dance. Similarly to MOI, the ERV must reach one of two nodes available to properly execute TEI, where one of these nodes represents a North injection and the other a South. However, it is unlikely that the ERV will be at or near one of these nodes at the instant the OS is captured. Therefore, the ERV must again use the nodal precession generated by the oblateness of Mars to align its orbit with one of the departure nodes. Once one of these departure nodes is nearly achieved, the ERV will begin its 3-burn scenario for departure, which is effective in reducing gravity losses, where the first burn raises the apoapsis to a 2-day period and nearly ceases nodal precession. Then, before departure, the second burn lowers the periapsis to 175 km, and finally the last burn provides for Mars escape. However, since nodal precession will not be completely nulled, the departure node should be biased, where the ERV should execute the first of the 3 burns when its node has reached a value that will perfectly align in the remaining time prior to departure with the minimum regression rate it now possesses in this large orbit. Then, to complicate things further, the ω of this orbit needs to be chosen wisely when executing the first burn in this departure scenario as well, as $\dot{\Omega}$ will also have an associated $\dot{\omega}$, and essentially only one value of ω allows both Ω and ω to be aligned using precession. If not given the proper value, it could take hundreds of years to actually match both the ω and Ω perfectly to the pair of specified values with natural precession alone. It is also important to note here that it cannot be assumed that perfect alignment and timing can be achieved. Therefore, propellent must be allocated such that TEI includes margin for an injection "window" (which may be needed to accommodate TEI over several days), as well as navigation ΔV to clean up any errors and dispersions from the final injection burn and/or variations in the final ω and Ω from ideal. At the point TEI is successfully performed, the arrival/departure dance can be said to be concluded, and the ERV can proceed on its way back to its native Earth.

Finding an Optimal Rendezvous Strategy

It would be favorable, in a strategy so very critical to mission success, if each portion of the rendezvous process could be achieved while requiring the absolute minimum amount of time as well as ΔV from both the MAV and the ERV. However, while indeed desirable, this is not realistically achievable due to several mission characteristics imposing constraints on the rendezvous strategy. These include: MAV injection errors, stay time at Mars, number of samples to be retrieved, and others specific to each unique mission architecture.

The idea of designing for the worst case scenario will be used to size the design of each mission element, equipping the mission with the ability to withstand all foreseeable variation in mission constraints over the mission architectures under consideration, and still achieve mission success. Of course, an equally pertinent objective will be to design a rendezvous strategy that yields the least harmful worst case events. That is, the strategy chosen should allow for the best, worst case, possibilities of delta-v and mass growth experienced by each spacecraft.

Incidentally, the only area of the arrival and departure dance that allows for implementing a substantial amount of strategic freedom is intermediate rendezvous. For instance, events such as Mars Orbit Insertion, aerobraking, OS detection, terminal rendezvous, and Trans-Earth Injection are all essentially fixed in their approach and required ΔV. It should also be noted that constraints such as MOI and TEI are driven by the mission architecture / opportunity, while all activities between arrival and departure are fairly "opportunity independent".

Only one requirement defines the level of success during intermediate rendezvous, and that is the degree to which the ERV has matched the OS's orbit. Therefore, it is inevitable that energy must be expelled by either the ERV or the MAV delivering the OS, or possibly both, as the ERV and OS will almost certainly not begin intermediate rendezvous in the same orbit. From this point, the dilemma is in deciding how much of this ΔV burden should be placed on each system.

Ultimately, the ΔV burden should be somewhat biased toward the MAV, as the ERV is more sensitive to growth per m/s of ΔV than MAV (or translated to the Lander). This is a result of the ERV's propulsion system size, as it is much larger in scale and thus more sensitive to propellent growth. However, it is also not wise to allow the burden of ΔV to fall too heavily on the Lander/MAV, as each kg added to the MAV requires increased mass on the Lander for additional support structure, thermal system, larger erection system, etc. This powerful "snowball effect" translates into approximately 1 kg of total Lander mass for every 1 m/s of ΔV added to the MAV. Moreover, current entry technologies limit the amount of mass that can be safely delivered to the surface or Mars.

As discussed earlier, the minimum altitude allowed for the OS orbit is found to be on the order of 350 km. Fortunately, this allows for some benefits to be shared by both the ERV and the MAV. That is, the GLOM of the MAV is reduced as much as allowed, the achievable differential node drift is increased to and save time during the node matching phase, and the ERV requires a reduced time (and possibly ΔV) in which to aerobrake as compared to a lower altitude rendezvous orbit. If, as a result of this strategy, the ERV and MAV (and thus Lander) masses are indeed minimized while still meeting all mission constraints, and enough propellant is on board each spacecraft to complete the "worst case" arrival/departure dance, the strategy can be said to be "optimized".

However, since aerobraking is not be available for phasing and orbit matching during the intermediate rendezvous of a second OS, it is be advantageous to maximize the amount of time available for the second rendezvous. Simply stated, the more time that is available for rendezvous, the less ΔV that is required. Yet, in designing for this second rendezvous, the time vs. ΔV analysis should be performed under the worst case of conditions, and even though the worst case ΔV occurs (in targeting the 350 km circular orbit) when the second OS is in a 250 km by 450 km elliptical orbit (illustrated in Figure 9 below), the most relevant trade here is not to consider the ΔV independently, but to instead trade the required ΔV with respect to the time required to align Ω of the two orbits. For this reason, the worst case scenario actually occurs when the second OS is in a 450 km circular orbit, since this orbit provides for a much slower precession rate and thus more ΔV from the ERV to create a satisfactory relative drift rate. This is shown in Figure 10 below.

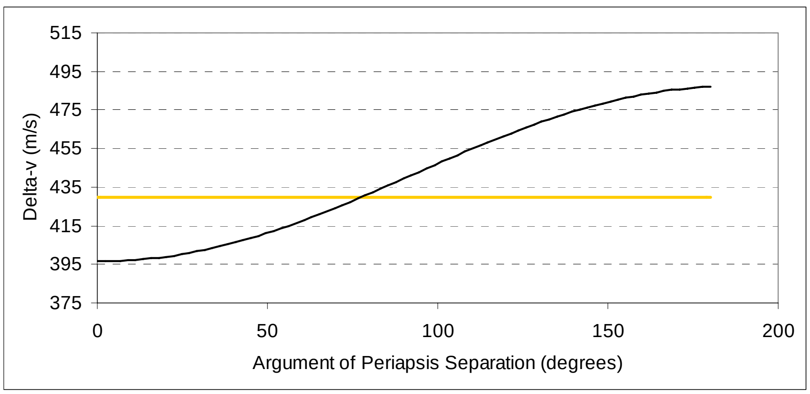


Figure 9: Here the argument of periapsis separation is varied between the 250 km by 450 km and a 250km by 3000 km orbit, and the delta-v that results from the transfer between them is shown by the black curve. Then, the orange curve shows the delta-v resulting from a transfer between a 450 km circular orbit and the same 250 km by 3000 km orbit. It is clear that the worst case delta-v occurs when the 250 km by 450 km orbit reaches a separation of 180 degrees.

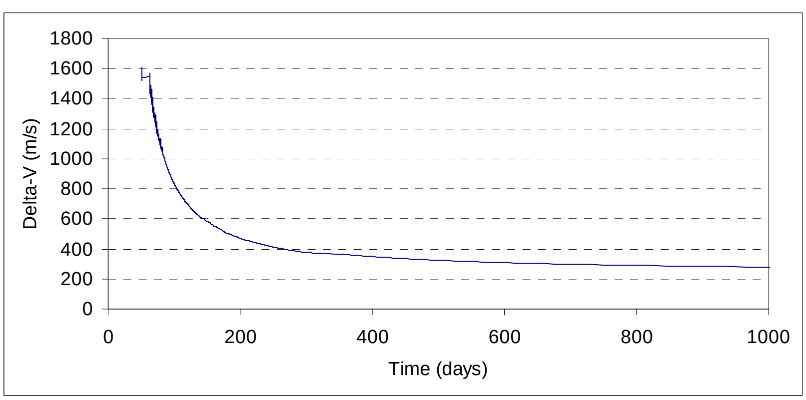


Figure 10: The time vs. delta-v required to align a 360 degree separation in the nodes between the ERV and the worst case orbit for the second OS (450 km circular orbit)

Example Architecture 1: Sending the Lander First

The first example architecture addressed here involves sending the Lander spacecraft to Mars in an opportunity prior to the ERV. The attractiveness of this architecture lies in that if the Lander is unsuccessful, the program will not lose the expense associated with launching the ERV, as there would be no need for an attempt to retrieve an orbiting sample that was not successfully placed into Mars orbit. The information provided below in Table 1, essentially establishes the framework of the mission and will act as a set of inputs to the arrival/departure dance.

Launch Period Characteristics	Lander #1	Lander #2	ERV	ERV Return
Launch Period	12/11/2015 - 12/20/2015	3/10/2016 - 3/29/2016	5/14/2018 - 6/2/2018	6/2/2020 - 6/11/2020
Arrival Date	9/9/2016	10/6/2016	12/31/2018	12/14/2020
Max C3	21.5	19	9.9	11.5
Departure Declination	4.6	46.6	28	31.1
Max Vhp	3.83	3.76	3.22	3.31
Arrival Declination at Mars	N/A	N/A	4.2	N/A
Trajectory Type	I	I	I	I
Stay Time (days)	1362	1335	519	N/A
Landing Site Access	~45N to 86S	~63N to 58S	N/A	~85N to 55S

Table 1: The trajectory characteristics for this mission are shown above, where the launch for Lander #2 only occurs if the project decides to pursue the option of a second OS. The launch periods were selected strategically to minimize MOI for the ERV, while providing the Landers access between 45S and 45N and a relative entry velocity less than 6 km/s. All trajectories here are type I. It should be noted that the launch for this second OS would experience performance degradation (5%-10%), since the DLA greater than 28.5 degrees (assuming Eastern Test Range launch).

As eluded to earlier, this architecture could potentially prove advantageous to the intermediate rendezvous optimization problem. While the landing site access requirement is still 45S to 45N, the latitude of the actual landing site(s) could be nearer to the Martian equator, which would enable the ERV to insert into a lower inclination since MOI would occur long after the Lander(s) arrive. Not only would this lower inclination provide faster precession rates for nodal alignment, it would also lower the performance requirement of the MAV. However, it should be noted, since the greatest arrival/departure declination at Mars is listed as 31.1 degrees above, the ERV's inclination could not be any lower than this value.

When launched, the MAV should insert the OS as closely as possible to the node predicted for the ERV after aerobraking. This orbit plane can, in fact, be anticipated, because the amount of precession that occurs during the ~6 month phase of aerobraking is nearly fixed, as is the insertion node at MOI. If the insertion is then performed successfully, a nodal phasing orbit may not even be required, and rendezvous could be completed in as little as 3 weeks. However, possible variations in the MAV launch period or window, as well as delivery dispersions of the MAV, complicate this strategy. With the dispersion in the semi-major axis of the 350 km circular orbit being +/- 100 km, the uncertainty in nodal precession is +/- 0.6 deg/day with a nominal rate of -7.6 deg/day. Further, with the Lander arriving 843 days prior to the ERV, the uncertainty in the node will grow to a magnitude of +/- 450 degrees before aerobraking even begins. Therefore, when the ERV enters its nodal phasing orbit, the node of the OS could be at any value between 0 and 360 degrees with essentially equivalent probability, and thus require up to 95 days to align Ω of the orbits. It should be noted that it would be advantageous, in terms of rendezvous, to simply delay the launch of the OS as much as possible to prevent the growth of nodal uncertainty. However, it is far too costly to design a Lander capable of surviving extended periods of time on the Martian surface, and also far too risky postpone the launch of a successfully collected sample.

Once nodal phasing has eliminated any plane separation between the orbits, and the aerobraking phase has reduced the ERV orbit apoapsis to the same level as that of the OS, the remaining orbital elements can be (nearly) matched propulsively. The worst case scenario, in terms of transfer ΔV, would occur if the launch dispersions resulted in producing a 250 km by 450 km elliptical orbit. For such an orbit, the ERV should perform the transfer once it has reduced its apoapsis to an altitude of 250 km as well. At this point, the transfer would require 82 m/s of ΔV, no matter the difference in the argument of periapsis between the OS and ERV orbits.

After orbit matching and OS retrieval, the ERV is prepared for departure, and since the proper departure phasing will not occur unitl June of 2020, the ERV is allowed 519 days of stay time. Of this stay time, ~180 days is dedicated to aerobraking and another 116 (worst case) to the capture of a single OS, leaving ample time for aligning the orbit with a proper Ω for departure. The nodes for departure range between 95 and 98 degrees for a North injection and -8 to -13 degrees for a South injection. Therefore, the worst case angular displacement that must be overcome by nodal precession is 278 degrees, which can be accomplished in 40 days at the slowest possible regression rate (450 km circular OS orbit). Finally, an additional day or more is required to perform the actual 3-burn TEI scenario. Thus, a comfortable margin on the order of ~182 days will remain, which, in turn, could be used for the capture of a second OS.

If a second OS is indeed pursued, the worst case ΔV required to perform intermediate rendezvous in the 182 days allotted will be 552 m/s from Figure 10 above, and the phasing orbit in which the ERV will be forced to reside in will be 250 km by 1630 km (worst case). A summary of this rendezvous, as well as the first, can be seen in Table 2 below.

THE DANCE: SUMMARY #1		
OS # 1	Nodal Phasing Orbit	250 km X 3000 km
	OS Orbit Targeted	350 km X 350 km
	Maximum Uncertainty in the Node	360°
	Maximum Time Needed for Nodal Alignment	95 days
	Maximum Time Needed for Rendezvous	116 days
	Maximum Rendezvous Delta-V	121 m/s
OS # 2	Worst Case Nodal Phasing Orbit	250 km X 1630 km
	OS Orbit Targeted	350 km X 350 km
	Maximum Uncertainty in the Node	360°
	Minimum Time Allowed for Nodal Alignment	161 days
	Minimum Time Allowed for Rendezvous	183 days
	Maximum Rendezvous Delta-V	552 m/s
	Maximum Time for Departure	41 days

Table 2: The above table summarizes the worst case scenario of rendezvous events possible for this architecture, and therefore the numbers which must be designed to.

Spacecraft Summary

In targeting the MAV to a circular orbit of 350 km altitude and 45 degree inclination, its resulting mass is about 300 kg, which translates into a total Lander launch mass of 3900 kg. Then, for the interplanetary trajectories detailed in Table 1, this mass requires the first Lander to launch on an Atlas V 541 (1% mass margin), and the second Lander on an Atlas V 551 (3.5% mass margin). Further, the mass and launch vehicle required for the ERV to successfully complete its mission can be observed in Table 3 below. This table indicates that retrieving one OS can be done fairly inexpensively, but the addition of the second requires a much larger launch vehicle.

ERV SPACECRAFT SUMMARY

Maneuver Description	OS #1 Delta-V (m/s)	OS #2 Delta-V (m/s)
Earth - Mars Cruise Allocation	30	
MOI into a 24 hr. Orbit	1268	
Aerobraking and Phasing	65	
Rendezvous	121	552
Terminal Rendezvous	40	40
TEI Maneuver # 1	1304	
TEI Maneuver # 2	3	
TEI Maneuver # 3	1213	
TEI Cleanup	30	
Earth Bias Maneuver	130	
Mars - Earth Cruise Allocation	30	
Total Delta-V	**4234.0**	**4826.0**
Total Launch Mass	**3176 kg**	**6126 kg**
Launch Vehicle Required	**Atlas V 521**	**Delta IV Heavy**
Margin	**15.7%**	**21.6%**

Table 3: This table summarizes the worst case performance of the ERV for example architecture 1.

Example Architecture 2: All Spacecraft in 2016

A second architecture option involves launching both the landing spacecraft and the ERV in the same opportunity. Those who favor this architecture bolster that the sample would be returned to Earth in a much shorter time following the first launch, in fact, over 2 years earlier than either of the other options presented in this paper. However, due to this quick turn-around time at Mars, the rendezvous process is much more time constrained and thus could potentially require much more ΔV for its successful completion.

Launch Period Characteristics	Lander #1	ERV	Lander #2	ERV Return
Launch Period	11/21/2015 - 12/10/2015	12/25/2015 - 1/13/2016	3/10/2016 - 3/29/2016	3/12/2018 - 3/21/2018
Arrival Date	9/12/2016	10/11/2016	10/6/2016	10/15/2018
Max C3	25.7	15.2	19	6.1
Max DLA	3.5	12.5	46.6	4.5
Max Vhp	3.81	3.72	3.76	3.18
Trajectory Type	II	II	I	I
Stay Time (days)	546	517	522	N/A
Landing Site Access	~45N to 87S	N/A	~63N to 58S	~85N to 45S

Table 4: This table shows the trajectory characteristics for the example mission architecture 2, where the process for trajectory selection is identical to that in Table 1. In order to satisfy all constraints, the 2016 trajectories were launched on type II trajectories.

The rendezvous strategy itself should be much like that explained in architecture 1, with the MAV targeting strategy being identical. Again, the Lander begins its 90 day mission immediately upon arrival, concluding it with a MAV launch and delivery of the OS into orbit. However, in this architecture, the amount of time between the launch of the MAV and the completion of the ERV's aerobraking phase is only be 120 days. Consequently, the total nodal precession uncertainty is more than +/- 87 (includes +/- 3 degrees from launch dispersions) degrees, and the ERV's stay in its phasing orbit is not as lengthy. Then, assuming the worst case, the maximum nodal drift to be overcome is 174 degrees, which will require a maximum of 46 days to align (minimum relative nodal walk of -3.8 deg/day). After the completion of rendezvous, only ~247 days of the 517 day stay time have been consumed.

The departure from Mars, in this architecture, occurs in March of 2018. After the OS is captured, the departure Ω needing to be aligned with ranges between 46 and 52 degrees for a North injection and -122 to -125 degrees for a South injection. Therefore, the worst case angular displacement that must be overcome by nodal precession is 192 degrees, which can be accomplished in 28 days at the slowest possible regression rate given by the 450 km circular OS orbit. Then, an additional day is required after this to perform the actual 3-burn injection scenario, but this is all that remains to be done at Mars at this point. Thus, a comfortable number of 241 days are still remaining for margin to the arrival/departure dance or for capturing a second OS.

When pursuing the second OS, its nodal uncertainty can be as much as 442 degrees [2(87°) + 2(3°+0.7*(120+67))]. Therefore, the ΔV required for this rendezvous can be determined by examining Figure 10, where the 241 remaining days necessitates 444 m/s.

THE DANCE: SUMMARY #2		
OS # 1	Nodal Phasing Orbit	250 km X 3000km
	OS Orbit Targeted	350 km X 350 km
	Maximum Uncertainty in the Node	174°
	Maximum Time Needed for Nodal Alignment	46 days
	Maximum Time Needed for Rendezvous	67days
	Maximum Rendezvous Delta-V	121 m/s
OS # 2	Worst Case Nodal Phasing Orbit	250 km X 1490 km
	OS Orbit Targeted	350 km X 350 km
	Maximum Uncertainty in the Node	360°
	Minimum Time Allowed for Nodal Alignment	220 days
	Minimum Time Allowed for Rendezvous	241 days
	Maximum Rendezvous Delta-V	444 m/s
	Maximum Time for Departure	

Table 5: The above table summarizes the worst case scenario of rendezvous events possible for this second example architecture, and thus, the design objectives.

Spacecraft Sizing

Since the MAV is again targeted to a circular orbit of 350 km altitude and 45 degree inclination, the Lander mass is equivalent to that of the first architecture. On their respective trajectories in this example, the margin will be 3.5% on an Atlas V 551 for Lander #1, and 2% on the same launch vehicle for Lander #2. The summary of the ERV spacecraft can be seen in Table 6 below, where either the first or both of the OS can be retrieved using an Atlas launch vehicle. It should be noted, however, that the total ΔV required for the example, as well as the ΔV for the second rendezvous, is less than that of the first. One result of this is the reduction of the launch vehicle needed to complete a rendezvous with the second OS.

ERV SPACECRAFT SUMMARY

Maneuver Description	OS #1 Delta-V (m/s)	OS #2 Delta-V (m/s)
Earth - Mars Cruise Allocation	30	
MOI into a 24 hr. Orbit	1574	
Aerobraking and Phasing	65	
Rendezvous	121	444
Terminal Rendezvous	40	40
TEI Maneuver # 1	1304	
TEI Maneuver # 2	3	
TEI Maneuver # 3	736	
TEI Cleanup	30	
Earth Bias Maneuver	130	
Mars - Earth Cruise Allocation	30	
Total Delta-V	**4062.7**	**4546.7**
Total Launch Mass	**2863 kg**	**4760 kg**
Launch Vehicle Required	**Atlas V 521**	**Atlas V 551**
Margin	**15.8%**	**1.2%**

Table 6: The above table summarizes the worst case scenario of rendezvous events possible for example architecture 2, and therefore the numbers which must be designed to.

Example Optimization 3: The ERV Launches First

The final architecture addressed here involves sending the ERV to Mars one opportunity prior to the Lander. In addition to simply arriving first, this architecture proceeds to place the ERV into a science or telecommunications relay orbit while it awaits its landing counterparts. The appeal of this particular architecture is derived from the additional utility it could provide the Mars Program as a whole, as either an additional science mission and/or an infrastructure asset. As an example, this architecture would also be advantageous to MSR itself in possibly providing additional data and information of the Martian surface to aid the Lander landing site selection process.

However, the arrival and departure dance takes on a much different form for such a mission, as instead of using aerobraking to create a nodal phasing orbit, the ERV must proceed to aerobrake and reduce itself to a much smaller, circular telecommunications orbit. The ERV will then reside in this 600 km altitude (exact orbital parameters are still available for trade) orbit, with a 45 degree inclination (to accommodate all possible landing sites), until the MAV has launched the OS. Therefore, the ERV would not benefit from re-initiating aerobraking during the intermediate rendezvous process, and the nodal alignment(s) will need to be created with propulsion.

Launch Period Characteristics	ERV	Lander #1	Lander #2	ERV Return
Launch Period	12/17/2015 - 1/5/2016	3/10/2016 - 3/29/2016	5/14/2018 - 6/2/2018	6/2/2020 - 6/11/2020
Arrival Date	9/30/2016	10/6/2016	12/31/2018	12/14/2020
Max C3	16.9	9.9	19	11.5
Max DLA	10	28	46.6	31.1
Max Vhp	3.67	3.22	3.76	3.31
Trajectory Type	II	I	I	I
Stay Time (days)	1341	519	1335	N/A
Landing Site Access	N/A	N/A	~63N to 58S	~85N to 55S

Table 7 The trajectory characteristics for this mission architecture, where the process for trajectory selection is identical to that in Table 1. To satisfy constraints, both trajectory types I and II were used here.

With the departure from Mars not occurring until June of 2020, the Lander's total stay time is going to be 519 days, where only a small portion of this time is used by the 90 day surface mission. When aligning for departure, the allowable departure Ω ranges between 95 and 98 degrees for a North injection and -8 to -13 degrees for a South injection. Therefore, the worst case angular displacement that must be overcome by nodal precession is 278 degrees, which can be accomplished in 45 days at a 600 km circular OS orbit. Then, an additional day is required after this to perform the actual 3 burn injection scenario, but this is all that remains to be done at Mars at this point. Thus, a comfortable number of 383 days remain for the capture of either one or two sample canisters.

As noted earlier, since it is more pertinent to save ΔV on the side of the ERV when considering rendezvous with the OS, and minimal amounts of the ΔV required for orbit matching can be saved using aerobraking, the semi-major axis and eccentricity to be targeted by the MAV should be chosen to reflect this. This is a major decision in the rendezvous strategy. The plots below qualify this statement by showing the patterns in ΔV and time resulting from various orbit selection. Figure 11 shows that, in fact, the more circular the orbit, the less ΔV required for the transfer and thus the more favorable option. Then, the actual time required for rendezvous is plotted against the associated ΔV in Figure 12.

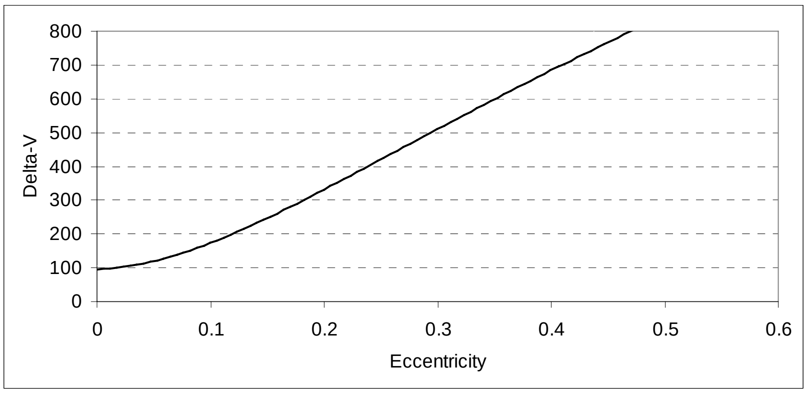


Figure 11: This figure shows the worst case delta-v required (180 degree separation in the argument of periapsis of the two orbits) to transfer the ERV from a 600 km circular orbit to an orbit with a semi-major axis of 3746.2 km. It can be seen in this figure that the more circular an orbit, the less delta-v required for the worst case transfer. This can be similarly deduced by examining Figure 6. It is worth noting however, that the more elliptical the orbit the less delta-v required on the MAV.

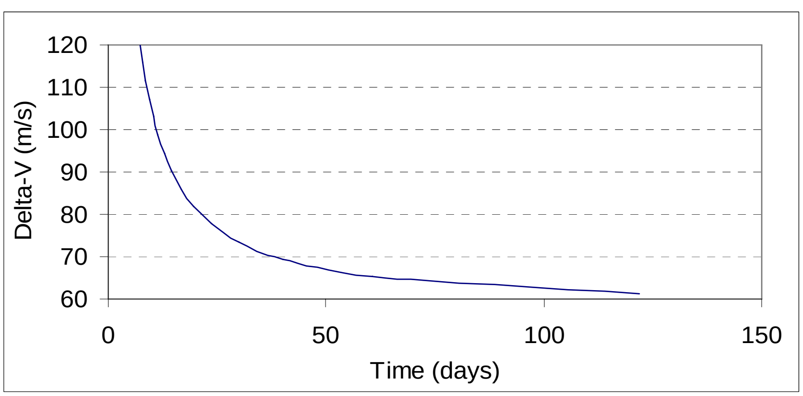


Figure 12: This is the time and delta-v required to match the orbit of the first OS, where the data is derived from the worst case dispersions on targeting circular orbits from 350 km to 500 km in size. The reason this looks so much different than the worst case delta-v vs. time for the first two examples (82 m/s no matter the time used) is because aerobraking is not being used.

However, this alone is not enough information to make a proper orbit selection for the MAV to target, and thus for rendezvous to occur, as the notion of a second OS has not yet been considered. That is, it would be advantageous to find a rendezvous strategy that yields the minimum ΔV available for rendezvousing with both OS in the allotted 383 days. This strategy, of course must cover the worst case scenario, where the worst case time and ΔV combination would result when the +/- 100 km MAV dispersions allow for the largest possible circular orbit. (i.e. a 450 km circular orbit when targeting for 350 km), as this results in the slowest nodal precession rate. Then, assuming the second OS also shares this same misfortune in its insertion, the result is the worst case ΔV possible for each rendezvous. Figure 13 below outlines these results, showing the total ΔV required to rendezvous with both the first and second OS (in 383 days), as a function of the targeted altitude of the circular OS orbit. What is more, it can also be seen that, during the 383 days allowed for rendezvous, a circular orbit of size 470 km should be targeted to give, the best, worst case scenario. The summary of the entire rendezvous process for this architecture can then be collectively observed in Table 8.

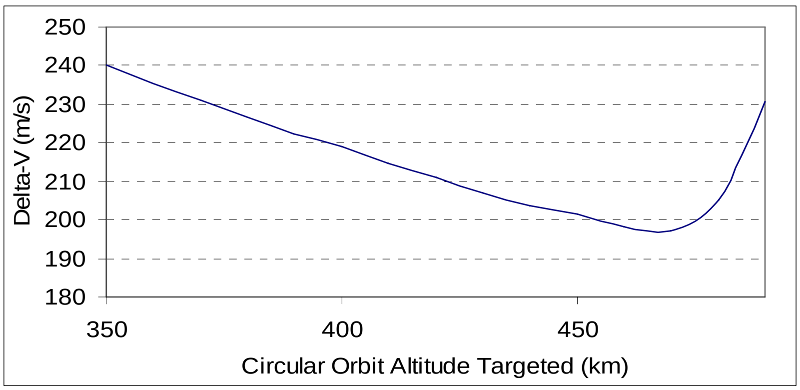


Figure 13: This plot shows the combined delta-v required for intermediate rendezvous with respect to the altitude of both the first and second OS. It is convenient to combine the two, as the time allocated to the rendezvous with the first OS directly affects the uncertainy, time allowed, and resulting ΔV for rendezvous with the second OS. It should be noted that the force driving the rendezvous ΔV to be much lower than the first two architectures is the reduced nodal uncertainty in each OS. This is due to the reduced time separating OS launch and the initialization of nodal phasing.

The DANCE: SUMMARY #3		
OS # 1	Nodal Phasing Orbit	600 km X 600 km
	OS Orbit Targeted	470 km X 470 km
	Maximum Uncertainty in the Node	6°
	Maximum Time for Nodal Alignment	40 days
	Maximum Time for Rendezvous	61 days
	Maximum Rendezvous Delta-V	70 m/s
OS # 2	Nodal Phasing Orbit	470 km X 630 km
	OS Orbit Targeted	470 km X 470 km
	Maximum Uncertainty in the Node	47°
	Maximum Time for Nodal Alignment	300 days
	Maximum Time for Rendezvous	321 days
	Maximum Rendezvous Delta-V	128 m/s
	Maximum Time for Departure	29 days

Table 8: The above table summarizes the strategy adopted for the worst case set of mission conditions for this third example architecture.

Spacecraft Summary

In targeting the desired circular orbit of 470 km altitude and 45 degree inclination, the resulting MAV mass increases to ~320 kg, which translates into a total Lander mass of 3980 kg. At such a mass, the first Lander could be launched on an Atlas V 531 with a margin of 8.4% to the required launch C3 of 9.9 km^2/s^2. Then, the second Lander would also be able to fit on an Atlas V 551 with a margin of less than 1%. Finally, the summary of the ERV designed for this architecture, can be observed in Table 9. Unfortunately, despite the fact that the dual OS rendezvous ΔV here outclasses both of the other options, this is not very apparent, as the ΔV requirements for MOI and TEI were more stringent for this example than either of the other two. While the rendezvous with the first OS is not much better than the other two, where Aerobraking + Intermediate Rendezvous + Terminal Rendezvous is only ~10 m/s less in this option, the rendezvous with the second OS provides immense savings (over 300 m/s). Therefore, for an arrival and departure dance that intends on returning both OS, this is the most favorably optimized architecture of the three example architectures.

ERV SPACECRAFT SUMMARY

Maneuver Description	OS #1 Delta-V (m/s)	OS #2 Delta-V (m/s)
Earth - Mars Cruise Allocation	30	
MOI into a 24 hr. Orbit	1543	
Aerobraking and Circularization	105	
Rendezvous	70	128
Terminal Rendezvous	40	40
TEI Maneuver # 1	1304	
TEI Maneuver # 2	3	
TEI Maneuver # 3	1213	
TEI Cleanup	30	
Earth Bias Maneuver	130	
Mars - Earth Cruise Allocation	30	
Total Delta-V	**4497.6**	**4665.6**
Total Launch Mass	**3923 kg**	**5223 kg**
Launch Vehicle Required	**Atlas V 541**	**Delta IV Heavy**
Margin	**8.7%**	**23.6%**

Table 9: The above table summarizes the worst case scenario of rendezvous events possible for this architecture, and therefore the numbers which must be designed to. Unlike the other architectures, the aerobraking phase also includes a circularization burn to achieve the telecommunications. However, it does not include the ΔV needed for raising and lowering periapsis for nodal phasing.

Conclusion

The Process outlined in this paper can serve as a method for optimizing the arrival and departure dance for many of the architecture trades available for Mars Sample Return. However, it is important to note that the trade space is still wide open for MSR, and new architectures will continue to surface and add new inputs to this optimization problem.

It is clear, however, that several key mission aspects act as drivers for the sizing of the mission elements and will do so in any architecture (although there is always the possibility of additional drivers). First, the energy requirements for MOI and TEI host a large portion of the total ΔV allocation for the ERV, where TEI is even more burdensome on the spacecraft sizing, as its propellant load needs to be carried throughout the majority of the mission's maneuvers. Secondly, the size of the orbit targeted by the MAV is essentially the only place to trade the mass of the Lander from a mission design standpoint, since it is the only time in which it performs any propulsive maneuvers (aside from Earth-Mars cruise), however it was also shown here that a m/s of ΔV on the MAV is not as harmful to the Lander as a m/s to the ERV. Thirdly, the nodal uncertainty accrued by the OS is very straining on the second rendezvous, where the third example architecture actually showed the benefits of eliminating this. Finally, the amount of time available also had a significant impact on the ΔV required to retrieve the OS where any rendezvous that did not include the use of aerobraking suffered accordingly. However, if a more stressing case were presented, the time available could also limit the extent aerobraking is usable for the capture of even the first OS, and thus affect the ΔV there as well.

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