Optimizing Mars Sphere of Influence Maneuvers for NASA's Evolvable Mars Campaign

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NASA's Human Spaceflight Architecture Team is refining human exploration architectures that will extend human presence to the Martian surface. For both Mars orbital and surface missions, NASA's Evolvable Mars Campaign assumes that cargo and crew can be delivered repeatedly to the same destination. Up to this point, interplanetary trajectories have been optimized to minimize the total propulsive requirements of the in-space transportation systems, while the pre-deployed assets and surface systems are optimized to minimize their respective propulsive requirements separate from the in-space transportation system. There is a need to investigate the coupled problem of optimizing the interplanetary trajectory and optimizing the maneuvers within Mars's sphere of influence. This paper provides a description of the ongoing method development, analysis and initial results of the effort to resolve the discontinuity between the interplanetary trajectory and the Mars sphere of influence trajectories. Assessment of Phobos and Deimos orbital missions shows the in-space transportation and crew taxi allocations are adequate for missions in the 2030s. Because the surface site has yet to be selected, the transportation elements must be sized to provide enough capability to provide surface access to all landing sites under consideration. Analysis shows access to sites from elliptical parking orbits with a lander that is designed for sub-periapsis landing location is either infeasible or requires expensive orbital maneuvers for many latitude ranges. In this case the locus of potential arrival perigee vectors identifies the potential maximum north or south latitudes accessible. Higher arrival velocities can decrease reorientation costs and increase landing site availability. Utilizing hyperbolic arrival and departure vectors in the optimization scheme will increase transportation site accessibility and provide more optimal solutions.

Nomenclature

a	=	Orbit semi-major axis
AOP	=	Orbit argument of periapsis
B-plane	=	Body Plane
ΔV	=	Change in velocity
e	=	Orbit eccentricity
EDL	=	Entry, descent and landing
EMC	=	Evolvable Mars Campaign
EUS	=	Exploration Upper Stage
i	=	Orbit inclination

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J_2	=	Planet second dynamic form factor
LAN	=	Orbit longitude of ascending node
LEO	=	Low-Earth orbit
LMO	=	Low-Mars orbit
μ	=	Planet standard gravitational parameter
n	=	Mean orbital motion
NASA	=	National Aeronautics and Space Administration
$\dot{\omega}_{J2}$	=	Rate of change of orbit argument of periapsis (rad/s)
$\dot{\Omega}_{J2}$	=	Rate of change of orbit longitude of ascending node (rad/s)
Rp	=	Planet equatorial radius
SEP	=	Solar Electric Propulsion
SOI	=	Sphere of Influence
V_∞	=	Hyperbola's velocity at infinity

I. Introduction

The Evolvable Mars Campaign (EMC) is an ongoing series of architectural trade analyses to define the capabilities and elements needed for a sustainable human presence on the surface of Mars. The Human Exploration and Operations Mission Directorate leads the campaign, with participation across nine NASA centers, and close coordination with other architectural analysis groups, the Science and Space Technology Mission Directorates and the Offices of the Chief Scientist and the Chief Technologist. The EMC routinely invites inputs from external organizations as well, including international partners, industry, academia, and NASA advisory groups.

The EMC identifies a set of operational capabilities and architectural trades required to sustainably expand human presence from low-Earth orbit (LEO) into deep space. The capability-driven EMC integrates science missions, robotic precursors, capability pathfinders, and a sustainable cadence of crewed missions and activities that lead to an extended human presence on the surface of Mars.

Several scenarios have been considered for a human mission to the Martian surface. Of these, only one spans all Mars vicinity destinations. The "Mars vicinity and Phobos, followed by mission to Mars surface" scenario represents an ambitious campaign that leverages most of the capabilities and potential tradeoffs described in the EMC. It acts as a point of comparison for future assessments and serves as the baseline reference for the EMC. This baseline scenario is then used to evaluate capabilities, schedules, risks, challenges, and mitigation strategies. To provide focus and to limit the possible alternatives, a set of ground rules and constraints were initially applied:

- Humans will travel to the Mars System by mid-2030s
    - Could imply orbital, Phobos/Deimos and/or surface expeditions
    - Mars mission opportunities throughout the 2030s will be evaluated to avoid overly restrictive mission availability
- Propulsion technology will utilize solar electric propulsion (SEP) systems extensible from the Asteroid Redirect Mission's robotic spacecraft bus
- SLS Block 2 launch vehicle will be available (4xRS25 Core + Exploration Upper Stage (EUS) + Evolved Boosters + 8.4 m or 10 m fairing)
- Orion spacecraft will be available
- SLS/Orion launch rate of one per year is sustainable in the Proving Ground
- Vehicle checkout/aggregation will be conducted in cislunar space to leverage infrastructure established during Proving Ground missions in the 2020s
- Human missions to the Mars system will be developed for four crew members
- Crew vehicle and transportation systems will be reused for sustainability and potential cost advantages when reasonable

The round trip transportation of crew and cargo between Earth and Mars has been studied since Apollo and remains a challenging problem. Over the past 30 years, several NASA Mars Design Reference Architecture studies[1,2,3,4] have investigated multiple propulsion technologies to meet the transportation requirements for a particular mission architecture. The most recent, Mars DRA 5.0 includes LEO aggregation, a 1-Sol Mars parking orbits, direct return to Earth in a capsule, and a surface infrastructure strategy which is duplicated at different landing sites for each mission. Propulsion system sizing is strongly coupled with transportation architecture, including deployment and return to Earth's sphere of influence (SOI), interplanetary trajectory design and operations in the Mars SOI. Surface infrastructure buildup options and site accessibility over multiple Mars opportunities also impact Mars in-space transportation options. Previous architecture studies have either made simplifying assumptions regarding the accessibility of landing sites across multiple opportunities or have not explicitly described the solutions developed for system reorientation and destination accessibility at Mars. The EMC differs from past studies as it utilizes cis-lunar space for aggregation, explores reuse of Mars transportation systems, and includes development of analytic solutions for Earth and Mars SOI maneuvers at different parking orbits. These solutions enable access to the Mars moons for early missions and to a Mars research station across multiple exploration opportunities later in the campaign. This paper describes ongoing method development and implementation for optimization of maneuvers in the Mars SOI to enable round trip piloted missions to Mars moons and Mars surface. Several realignment strategies have been proposed in the past, the apotwist[5], free apotwist which sets the SMA and inclination of the elliptical parking orbit such that it processes from the arrival orbit to the departure orbit orientation[6], off periapsis apotwist[7] and non-perigee, non-tangential arrival and departure[8]. These methods are used as a starting point for the orbital realignment solution development. The ongoing effort in EMC implements and extends them to enable development of solutions that reduce ΔV for taxis to Mars' moons, sites accessible for piloted lander departure and EDL, and for two modes of ascent. The goal of these activities is development of integrated solutions that balance performance requirements for transportation segments in Mars architectures. This facilitates both improvement of those architectures and comparison of feasible or "closed" architecture options that meet the Evolvable Mars Campaign objectives. Section II. describes the in-space transportation architectures currently being assessed within the EMC. Section III. describes the Mars SOI problem and initial assessments of round trip orbital missions. Section IV. delineates considerations and costs associated with round trip visits to Phobos and/or Deimos. Section V. discusses Mars surface mission considerations, constraints, initial findings and additional degrees of freedom explored to enable repeated access to the same site across multiple opportunities. Finally section VII. provides conclusions and planned next steps for developing more optimized Mars SOI plans and element performance allocations.

II. Transportation Architectures

Pre-deployment mission strategies, often termed "split mission", have been used in previous Mars architectures to preposition the assets needed for destination operations, and/or the return trip home. One of the advantages of this approach is that it reduces the piloted spacecraft size and therefore propellant and power requirements at the expense of additional cargo spacecraft. The cargo spacecraft can use interplanetary trajectories or propulsion systems that are more efficient. Disadvantages of the split approach include the additional complexity of the rendezvous with the pre-deployed assets increasing the risk to the mission or crew if rendezvous is unsuccessful. Additionally, the split approach increases the dormancy requirements on the systems and can lead to multiple transportation system developments. For the EMC, two different split mission approaches are being developed that utilize different methods of combining solar electric and chemical propulsion. Both mission approaches utilize pre-deployed destination systems in a "split mission" manner; the Split SEP-Chemical option also includes a "split piloted mission" where the return propulsion systems for the crew is also pre-deployed at Mars.

Both EMC transportation architecture options use chemical propulsion to supplement the high-efficiency, low-thrust electric propulsion systems. While low-thrust electric propulsion is a higher efficiency propulsion system on the basis of propellant usage, the lower thrust levels associated with these systems at currently assumed power levels significantly extends transit times. To reduce flight times, high-thrust chemical propulsion or aerocapture is used in the EMC architectures to supplement the electric propulsion systems within Earth and Mars gravity wells.

A. Split SEP-Chemical Approach

In the Split SEP-Chemical approach[9], solar-electric cargo spacecraft are used to pre-deploy both destination systems and the chemical return stage(s) prior to crew Earth departure. The pre-deployment flights use a single SLS launch to an elliptical orbit followed by a SEP Earth spiral to escape. The SEP then performs the transit to Mars and drops off the payload for capture into the Mars SOI. Landers then aerocapture at Mars, while other destination systems and chemical return stages propulsively capture into Mars parking orbits. After pre-deployment is completed, the crew travels to Mars in an in-space transit habitat propelled by a pair of chemical propulsion stages; one for Earth departure and the other for Mars arrival. The EMC chemical propulsion stage concept uses liquid methane and liquid oxygen as propellant. This stage relies on the same engines that are used for the EMC Mars descent and ascent vehicles, leveraging engine commonality to reduce development costs, but pushing those costs earlier in the development timeline. These stages require long-duration cryogenic propellant storage and enable faster transfer times than the SEP spacecraft used to pre-deploy cargo, which transit to Mars in three to five years. In this approach, the crew vehicle must rendezvous with the Mars departure and Earth capture chemical propulsion stages in Mars orbit to return to Earth. While this does impact overall mission risk, the pre-deployment of Earth return propulsion greatly reduces the Earth departure mass of the crew stack for the mission by placing more of the Mars delivery mass burden on the higher-efficiency SEP propulsion spacecraft.

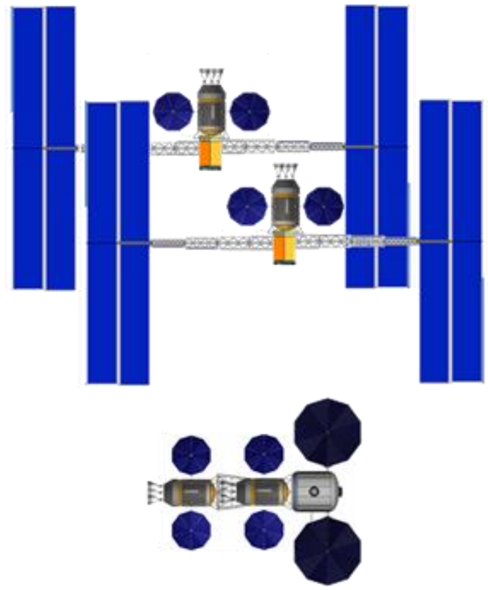


Figure 1. Transportation elements for the piloted Split SEP-Chemical architecture, pre-deploy SEP and chemical stacks and piloted Earth departure stack. with habitat.

B. Hybrid Approach

In the Hybrid approach[10], the cargo and crew transportation systems have a common design, requiring only one Mars-capable in-space transportation vehicle to be developed. The hybrid propulsion system combines SEP with small chemical engines that are used at key points in the mission design to reduce power levels that would result from a purely SEP approach with the same time of flight. The piloted hybrid spacecraft consists of an integrated habitation module and the hybrid propulsion system. In order to launch the pre-integrated habitat and transportation stack, refueling and logistics supply are needed prior to its' first trip to Mars. The Hybrid spaceship does not stage any of the propulsion system and can be refueled and reused for multiple trips to Mars after return to cis-lunar space. At Earth departure it includes enough propellant and logistics for one piloted round trip Mars orbit mission. In cargo mode, the hybrid propulsion system delivers the destination systems to Mars orbit, returns to Earth without payload, and captures into cis-lunar space for reuse. The EMC hybrid propulsion system concept uses existing storable chemical propulsion systems and Asteroid Redirect Mission SEP components. It requires development of refueling capabilities for nitrogen tetroxide, monomethyl hydrazine, helium, and xenon, as well as development of a refueling tanker system that is either launched on an SLS or provided by commercial and international partners[11].

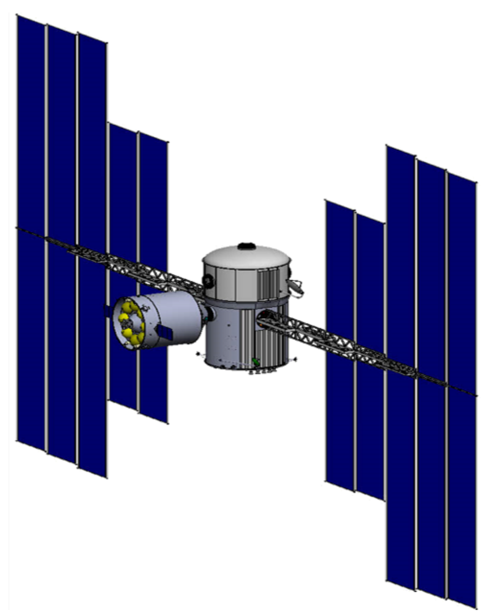


Figure 2. A tanker refuels the integrated habitat and Hybrid Propulsion Module before Earth departure.

III. Mars Sphere of Influence Analysis for EMC

For in-space transportation architectures, the choice of parking orbit determines how deep into the Mars gravity well the habitat and transportation system have to travel and sets the insertion and departure ΔVs. The parking orbit also sets the boundary between destination system transport (lander, ascent, and orbital taxi) which drives the ΔV for those system's delivery as well as their mission operations and crew support durations. Past studies have assumed either a 1-Sol orbit, low Mars orbit (LMO), or direct entry and landing. The SEP-Chemical transportation architecture uses minimum energy conjunction class trajectories for piloted missions to Mars and traditional 1-sol Mars parking orbit. However the return stages must be pre-deployed to Mars, requiring additional rendezvous in the Mars system to enable crew return to Earth. The Hybrid transportation architecture uses SEP to reduce arrival V_∞ and uses larger Mars parking orbits that are 5-sol to decrease insertion and departure ΔV. This allows the Hybrid to use a single spacecraft that travels round trip between cis-lunar space and Mars without staging any part of the propulsion system. For the Hybrid architecture, orbit realignment and destination accessibility are concerns since a parking orbit of this size has not be proposed before. Therefore initial evaluations have focused on the Hybrid and are the main focus of this paper. The initial step for the EMC architectures was the development of methods for assessment of a parking orbit realignment for round trip orbital missions that only evaluates the on orbit realignment strategy. These are useful for orbital only missions or cargo missions where a reusable transportation system is delivering an asset (lander or taxi) and returning to Earth years before the asset must be aligned for rendezvous.

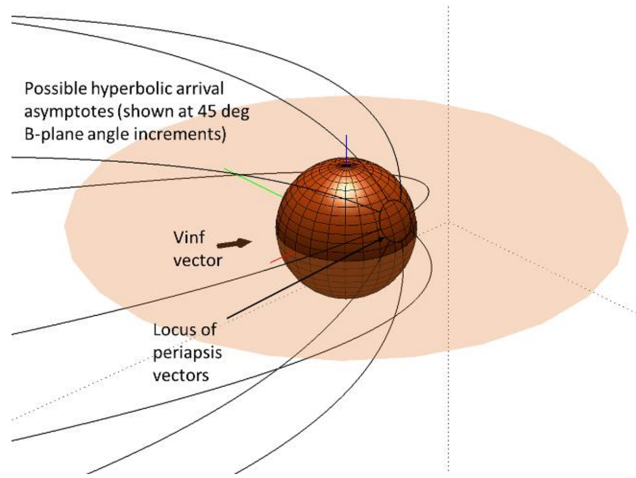


Figure 3. Locus of periapsis vectors for varied B-plane arrivals at Mars with a fixed V∞.

The incoming declination of an arriving spacecraft with respect to Mars's equator is determined by both the heliocentric trajectory and the season of arrival. Mars has a 25 degree axial tilt so the seasonal variation in declination of the same incoming trajectory in a sun ecliptic frame can be as much as 25 degrees relative to Mars equatorial plane. For Hybrid Mars arrival, the incoming declinations vary from -16 degrees to 25 degrees and the departure declinations vary from -17 degrees to 4 degrees for opportunities between 2039 and 2056. For Split SEP-Chemical Mars arrival, the incoming declinations vary from -33 degrees to 38 degrees and the departure declinations vary from -29 degrees to 29 degrees. At Mars arrival there are a set of locations where a tangential co-apsidal insertion can occur; this is the locus of possible periapsis locations for varied incoming B-plane angle. Choosing the arrival B-plane angle sets both the location of perigee and the inclination of the parking orbit. Figure 3 shows an arrival at Mars with possible hyperbolic arrival asymptotes at 45 degree B-plane increments and corresponding locus of periapsis vectors. The arrival V_∞ vector represents the magnitude and direction of arrival from heliocentric space. The latitude of the center of the locus is set by the arrival declination, which is set by Mars axial tilt and the heliocentric arrival vector. The locus for both arrival and departure vectors, set by the heliocentric trajectories, dictates all the possible arrival and departure parking orbits achievable with tangential co-apsidal insertion for a given round trip opportunity. Depending on the chosen orbital realignment method, and accounting for the effects of orbital precession, not all possible periapsis vectors enable realignment from the arrival orbit to the departure orbit.

Precession of orbits at Mars can be leveraged to enable orbit realignment while keeping the spacecraft in a fixed size orbit. The oblateness of Mars causes nodal regression: precession of the longitude of ascending node (LAN) and argument of periapsis (AOP). For highly elliptical orbits such as those currently considered for the EMC (1-sol and 5-sol), the J_2 contribution to precession is adequate for modeling purposes. For smaller orbits, higher J terms must be considered. Equation 1 shows the equations governing precession based on J_2. Once the semi-major axis (a) and eccentricity (e) are set, the only other independent variable that effects precession is the orbit inclination (i). As elliptical parking orbits become larger, precession decreases due to the presence of both a and e terms in the denominator of the equations. LAN decreases (moves westward) for prograde inclinations and increases (moves eastward) for retrograde inclinations. Thus, if the departure orbit is westward of the arrival orbit then a prograde inclination will move towards alignment of periapsis vectors and vice versa. The apsidal precession moves in the direction of the bodies' revolution.

$$\dot{\Omega}_{J_2} = -\frac{3}{2} n \frac{J_2 R_P^2}{a^2(1-e^2)^2} \cos i$$

$$\dot{\omega}_{J_2} = \frac{3}{4} n \frac{J_2 R_P^2}{a^2(1-e^2)^2} (4 - 5 \sin^2 i) \qquad (1)$$

- $\dot{\Omega}_{J2}$ = rate of change of orbit longitude of ascending node (rad/s)
- $\dot{\omega}_{J2}$ = rate of change of orbit argument of periapsis (rad/s)
- μ = gravitational constant = 42,828.314 km^3/s^2 for Mars
- R_P = planet equatorial radius = 3,396.2 km for Mars
- J_2 = J2 zonal gravitation term = 1.96045e-3
- n = mean orbital motion = μ/a^3
- a = orbit semi-major axis
- e = orbit eccentricity
- i = orbit inclination

The difference between prograde and retrograde behavior is important because there are groups of prograde and retrograde solutions for reorientations schemes that use apotwist maneuvers.

The first reorientation technique developed was a set of maneuvers termed the "Butterfly" (Figure 4) that uses third body effects and SEP thrusting near the edge of the Mars SOI for alignment.[12,13] The chemical propulsion system provides 0.065 km/s from the 5-Sol parking orbits to reach the edge of Mars SOI where small maneuvers with the SEP will reorient the orbit before the chemical system provides another 0.065 km/s to re-capture into the departure parking orbit. The duration of the butterfly maneuver varies between 100 and 250 days; however the required ΔV is relatively independent of duration.

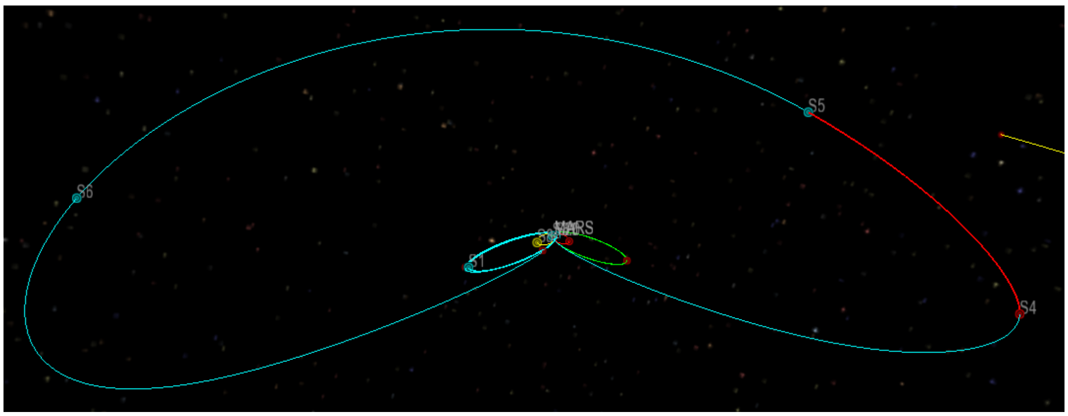


Figure 4. Butterfly reorientation maneuver.

The second reorientation technique developed began with an apotwist reorientation. For the apotwist there are 3 boundary conditions; the arrival and departure vectors and the stay time between the arrival and departure. With a fixed parking orbit size (*a* and *i*), a search for parking orbit geometries is performed that allows tangential arrival and departure with a single intermediate plane change that twists the orbit around the line of apsides. Once the initial orbit is established, it will precess forward in time until the twist point where the plane change maneuver occurs. Then the post-twist orbit will precess such that it is correctly aligned for a tangential departure at the desired departure time. The apotwist method was used for a preliminary assessment of both the Hybrid and Split SEP-Chemical architectures. Apotwist results can be found in Appendix A, detailing arrival inclination on the Y-axis, departure inclination on the X-axis and total twist ΔV as the color of the marker. For the Hybrid, limited solutions exist with low realignment ΔV and many departure parking orbit options are highly retrograde. No solutions were found in 2039 or 2043. More apotwist realignment solutions exist for the Split SEP-Chemical architecture for 2033, 2039 and 2043 opportunities, but realignment ΔV on the order of 0.8-0.9 km/s is required for low inclination prograde arrival orbits and departure orbits are highly inclined prograde or retrograde. Thus, the apotwist offers limited degrees of freedom and does not enable mission design with favorable parking orbits at Mars.

The next step in method development was addition of bi-elliptic transfers to the apotwist realignment strategy. The bi-elliptic apotwist increases the number of degrees of freedom from three to five. For this problem the boundary conditions are the same as those of the apotwist. A parking orbit size as well as arrival and departure transfer orbit sizes are chosen: for the Hybrid these are a 5-Sol parking orbit and 10-Sol transfer orbit, while for the Split SEP-Chemical they are a 1-Sol parking orbit and a 10-Sol transfer orbit. Increasing the transfer orbit size allows for reduction of the bi-elliptic transfer orbit plane change ΔV at the cost of one transfer orbit duration at arrival and departure. The method searches for solutions that allow a bi-elliptic three burn arrival, intermediate apotwist, and a bi-elliptic three burn departure. This leads to a total of up to seven burns, three of which are plane changes around the orbit line of apsides. The approach implemented for the solution space search uses random initial guesses for the five independent variables: twist time, hyperbolic arrival and departure B-plane angles, and arrival and departure parking orbit ascending nodes. With those initial guesses a gradient based optimizer evaluates the solution space with a constraint at the twist time that drives the difference in the periapsis vectors to near zero.

Figure 5 is a graphic depiction of one bi-elliptic apotwist solution for the Hybrid Architecture. The spacecraft arrives at Mars on orbit A, the incoming hyperbolic vector. Burn one places spacecraft onto transfer orbit B that takes it out to apoapsis, where a plane change maneuver changes the plane to orbit C. On orbit C, the spacecraft transfers back to periapsis where burn three occurs to insert it into parking orbit D. The spacecraft stays in parking orbit D and it precesses to orbit E at the twist time. Burn four is an apotwist plane change at apoapsis that places the spacecraft onto orbit F which is the post twist orbit. Orbit F then precesses to orbit G, the departure parking orbit. For departure the bi-elliptic arrival process is reversed with burn five to raise the apoapsis to transfer orbit H. Burn six changes the plane at apoapsis onto orbit I, the inbound transfer orbit. At Mars departure orbit I is in plane with the hyperbolic departure asymptote. Finally, burn seven places the spacecraft onto the hyperbolic orbit J. The results for both Hybrid and Split SEP-Chemical architectures show a broader range of inclinations at arrival and departure are possible, and more solutions with prograde departure orbits exist. These two reorientation schemes were used to assess orbital missions to Phobos and Deimos and destinations on the Mars Surface. Results are presented in Appendix B and Appendix C with description in sections IV. and V.

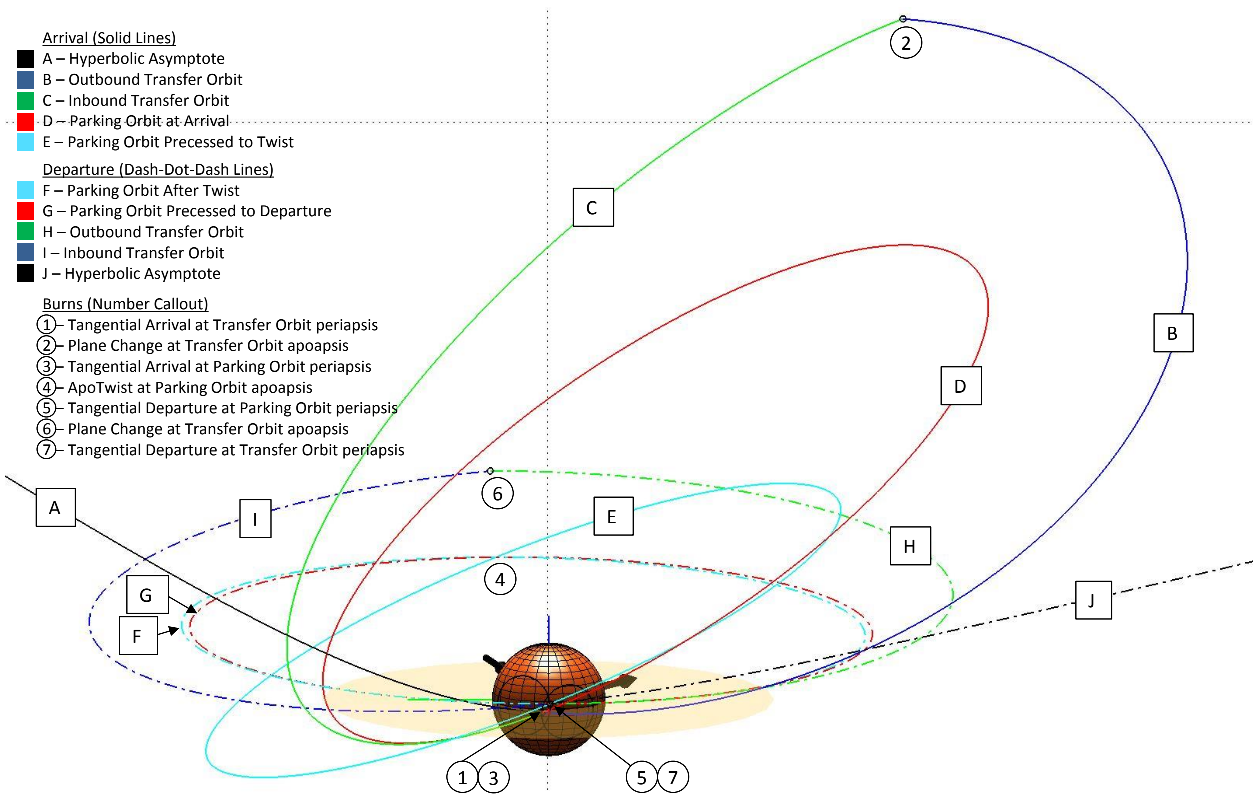


Figure 5. Bi-elliptic apotwist concept of operations.

IV. Mars Orbital Missions

Once the first two methods for realignment were developed and verified, the integrated mission design for Hybrid Mars moons orbital expeditions was examined. Initial investigations were for Phobos, followed by options for Deimos, and a tour of Phobos followed by Deimos. The taxi cost for rapid crew access was assessed for both short (<30 days) and long (>30 days) duration missions. For short missions, the taxi transfers between the destination and the arrival parking orbit for early missions (those occurring early in the time the crew is in the Mars SOI) and the departure parking orbit for late missions. These short missions allow for a butterfly realignment if desired, as the total stay time in Mars SOI is ≥ 300 days, while the longest butterfly maneuvers were on the order of 250 days. To minimize the taxi propellant for these cases, the arrival and departure B-plane angles are chosen such that the

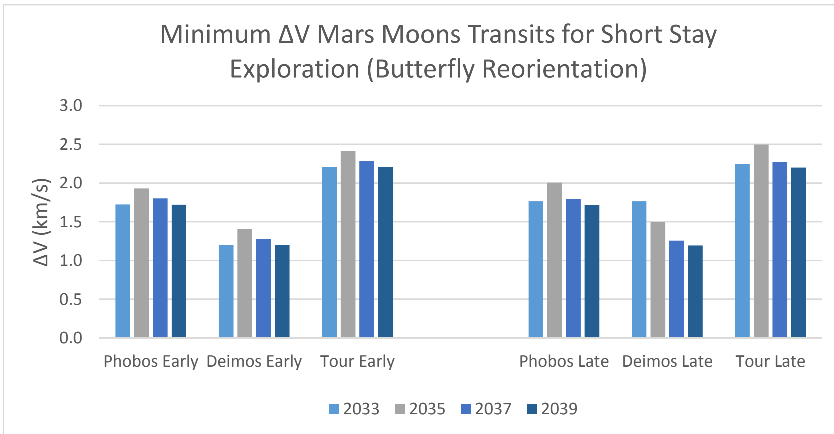


Figure 6. Short stay orbital mission taxi ΔV for butterfly reorientation.

transfer ΔVs are minimized. Figure 6 shows the minimum ΔV for transits using these parking orbits that assume a butterfly maneuver for realignment. For the Phobos and Deimos tour, the outbound transfer to Phobos is added to a transfer between Phobos and Deimos and then a transfer back to the original parking orbit from Deimos. For short expeditions to Phobos or Deimos a 2.0 km/s taxi budget is sufficient; for a tour of both Phobos and Deimos in a single expedition a 2.5 km/s taxi budget is needed.

For long stay options the butterfly maneuver is not acceptable due to the desire for the option to abort back to the in-space transportation system during the expedition. Bi-elliptic apotwists were calculated for opportunities from 2033 through 2058 for the Hybrid architecture since they remain in 5-sol parking orbits for the duration of the stay at Mars. Since the optimal combination of arrival and departure parking orbits cannot be determined analytically yet, the solution set is plotted to evaluate favorable cases. Figure 7 shows solution sets for 2033 with the taxi ΔV on the Y-axis and the apotwist ΔV on the X-axis. The apotwist ΔV is the penalty above a co-apsidal tangential arrival and departure for reorientation. Appendix B includes solutions for 2033 – 2037. As expected there are significantly more reorientation solutions for the bi-elliptic apotwist when compared to the apotwist. Favorable solutions are those in the lower left hand corner of these data sets with 0.15 km/s or less for the bi-elliptic apotwist maneuvers and with 2.0 – 2.25 km/s for the taxi to Phobos or Deimos, or with between 2.4 km/s and 2.7 km/s taxi transfer budget for a tour of both.

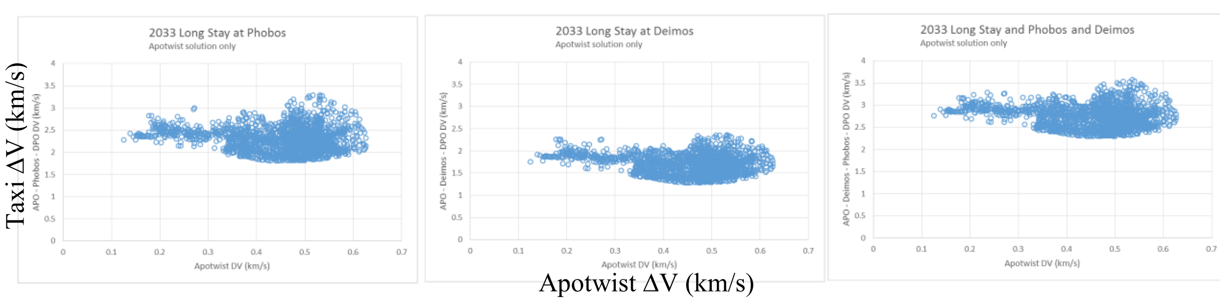


Figure 7. 2033 Long stay orbital mission taxi ΔV options for bi-elliptic apotwist.

V. Mars Surface Missions

There are two options for Mars surface access that are being evaluated for the Hybrid architecture as part of the EMC in 2016. The first is the EMC point of departure; it includes landing a partially fueled oxygen/methane ascent vehicle with ascent oxidizer provided by ISRU on the surface of Mars. The second option is similar to the recent approach proposed by Price.[14] The ascent stage ascends to LMO and rendezvous with a pre-deployed taxi; that taxi provides propulsion for the second segment of the ascent to the interplanetary transit vehicle in its departure orbit. This second mode of operations was the initial focus for the Mar SOI surface access and return method development due to concerns about the complexity of adding a rendezvous during ascent. Since the durations for surface stay vary across mission options and opportunities, the butterfly realignment approach was not used for surface missions. Only approaches that maintain the parking orbit size across the mission are considered to enable abort assessments after nominal mission assessments are complete. For both options the EDL system has the same constraint that the landing site on Mars is "under" the parking orbit periapsis. After egress from the heliocentric transportation system the lander performs a de-orbit burn at apoapsis onto a Hohmann-like descent transfer orbit to the surface (Fig. 8). At entry interface, all aero-assisted cross range and downrange capabilities are reserved for precision landing. This creates a constrained Mars arrival problem that differs from past studies. The NASA 90-day study[1] assumed that "Aeromaneuvering of the lander provides cross-range landing capability to reach an out-of-plane landing site." The EMC EDL constraint results in the periapsis locus establishing the range of achievable landing latitudes for tangential arrival burns, with the northern-most and southern-most points of the arrival locus spanning the range of achievable latitudes. For EMC piloted missions ascent to the transportation system parking orbit has been assumed due east and co-planar for latitudes up to 30 degrees. As this is an initial feasibility study, the methods developed for the coupled parking analysis are used to evaluate both the on-orbit realignment and the descent and ascent mission segments, including either due east ascent or north of east ascent, to understand the impact of additional ascent flexibility. Given this set of constraints a good solution for the bi-elliptic apotwist is not necessarily a sufficient solution when considering coupled on-orbit realignment with a specific surface location for the descent and ascent mission segments.

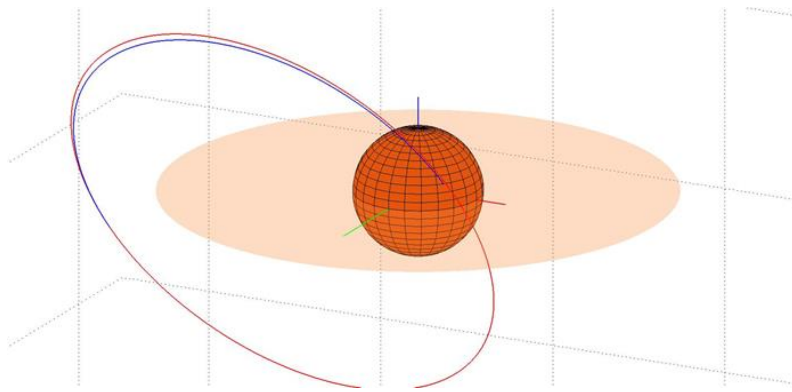


Figure 8. Sub-perigee landing geometry.

A. Bi-elliptic Apotwist Solutions

The bi-elliptic apotwist method, when applied to the early 2016 Hybrid architecture arrival and departure V_∞ vectors, provides solutions that cross a wide range of latitudes and a range of parking orbit inclinations; it also provides low ΔV options for interesting landing locations with low inclination departure parking orbits. Figure 9 is a plot of the 2039 Hybrid bi-elliptic apotwist solution. Alignment cost is represented by color, the X-axis is landing latitude and the Y-axis is the departure parking orbit inclination. For ascent, the departure parking orbit should be prograde; in the best cases its inclination is near the latitude of the landing site to minimize ascent and taxi vehicle ΔV. The dark blue solutions are favorable and show for this opportunity there are sites between 8 degrees South and 15 degrees North that can be accessed with minimal realignment cost.

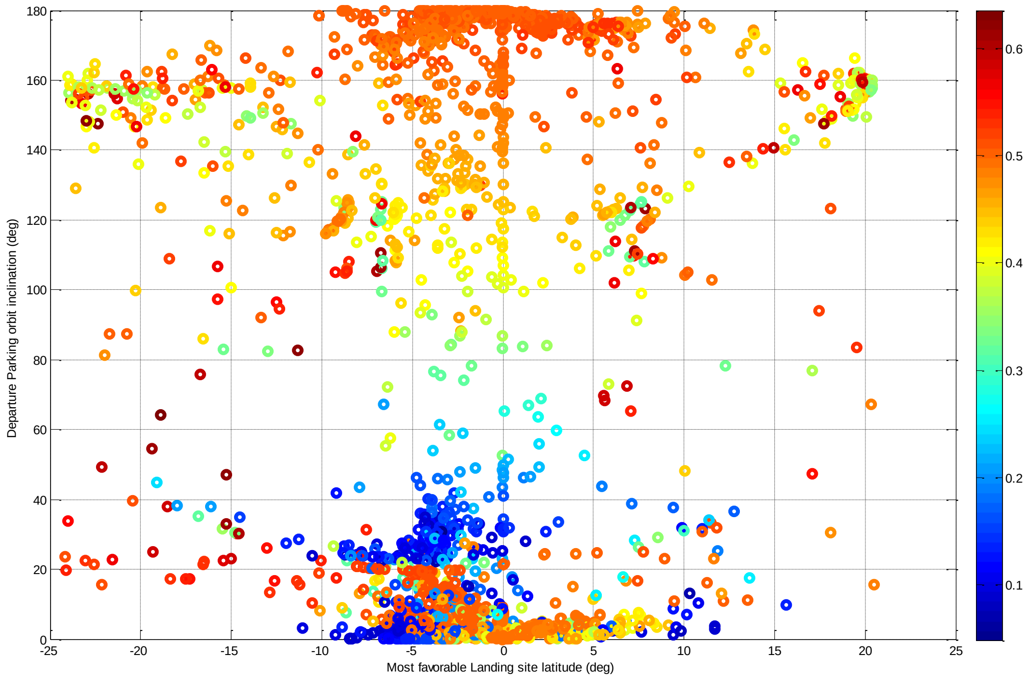


Figure 9. 2039 Hybrid bi-elliptic apotwist solutions.

Solutions for both the Hybrid and Split SEP-Chemical architectures were generated across a multi-decade period to understand the impact of the variation of arrival focus size and location across multiple opportunities. Appendix C includes the data sets specific to the Hybrid architecture; note that the X-axis scales vary from plot to plot. For these cases the lowest realignment ΔV solutions are the cases considered feasible. The total combined arrival and departure ΔVs for the Hybrid are approximately 0.5 km/s[15] and the Split SEP-Chemical trajectories are approximately 1.7-2.5 km/s[9]. Specific realignment ΔVs carried in architecture closure at this point in time were 0.15 km/s for the Hybrid and 0.3 km/s for the Split SEP-Chemical, with 5-Sol intermediate transfer orbits for bi-elliptic reorientation. There are ample solutions for the Hybrid with the exception of 2045 which requires a realignment budget closer to 0.35 km/s. However, when these data sets were plotted to show the accumulated intersection of the accessible latitudes, the number of solutions with common accessible latitudes decreases from 2039 until 2050 where the bi-elliptic apotwist solutions do not overlap.

B. Expanding Degrees of Freedom for Mare SOI Solution Sets

The Hybrid in-space transportation architecture with the EMC lander constraints and bi-elliptic apotwist does not provide sufficient flexibility with respect to accessible landing sites. Several options were identified to increase accessible sites; they can be categorized as either changes to the in-space transportation system or the lander architecture. For in-space transportation, adjusting the arrival V_∞ and declination with interplanetary systems or providing additional freedom in the realignment apotwist method and a significantly higher ΔV budget could provide flexibility. There are also options available that change the in-space transportation architecture even more, but they also impact the lander architecture: examples include aerocapture into LMO or changing the parking orbit to LMO from the higher parking orbits. With a low circular orbit, the periapsis vector no longer constrains landing latitude because the deorbit burn can occur at any point on the circular orbit. Thus, the lander could reach any latitude that is less than the parking orbits inclination. However there are potentially significant performance costs associated with going to LMO.

Another option is to change the lander architecture. The lander could utilize its inherent lift / drag capability to increase down-range or cross range capabilities so that landing does not have to be precisely sub-periapsis. Skip maneuvers or single pass capture to LMO and then descent from LMO are also options. Figure 10 illustrates the possible flexibility LMO provides for the Hybrid architecture. It shows the accessible latitude and bi-elliptic apotwist cost across opportunities, but does not take into account any additional penalty on the lander for passing through LMO on the way to Mars' surface. Lander architecture change remains an option for enabling site accessibility, but further exploration of in-space transportation realignment options is needed to quantify the cost of maintaining the current EMC EDL and Ascent constraints.

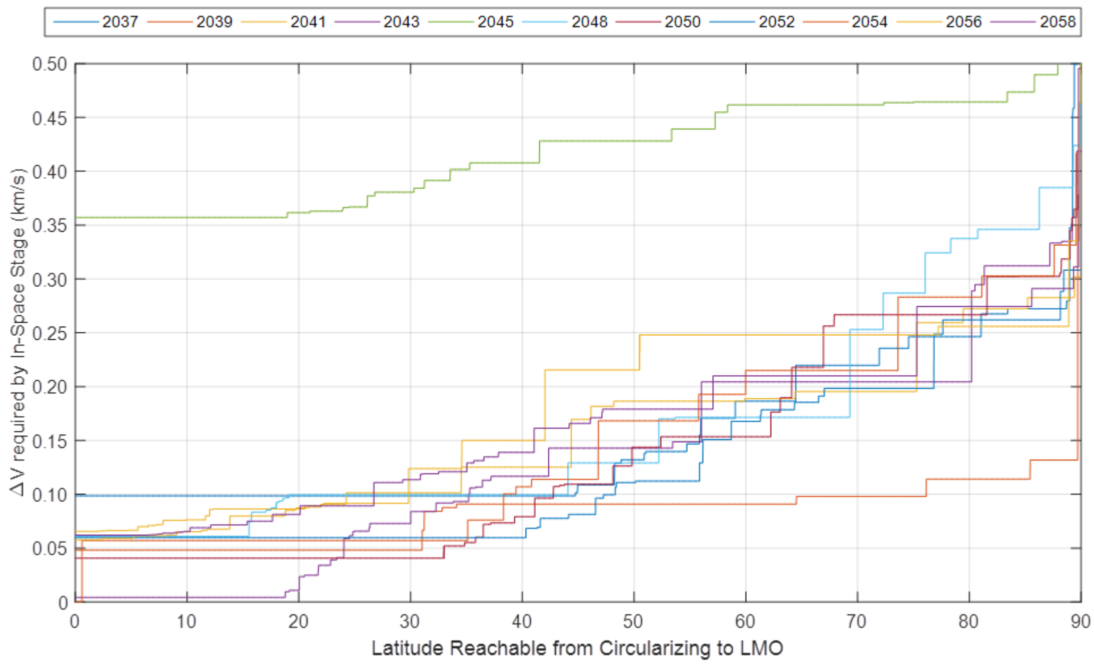


Figure 10. Site Accessibility with lander circularization to LMO.

C. Latitude Constrained Bi-elliptic Apotwist Solutions

A more focused approach to the reorientation searches was implemented that enables exploration of reorientation for a single latitude of interest at a time. The arrival B-plane angle is set rather than being an independent variable, enabling 4 variable searches over options with only B-plane angles that intersect the latitude of interest. These solutions are constrained to two points on the arrival locus where the latitude crosses. For the initial cases Jezero Crater was selected (18.8 degrees North); it is a target on the list of sites of interest[16] and is at a relatively low latitude.

Changes in the Hybrid transportation stack mass due to refined estimates of the habitat and logistics masses cause changes in the arrival and departure hyperbolic asymptote vectors, and correspondingly the size and orientation of the locus of periapsis vectors possible. The data in Fig. 11 correspond to these updated mass estimates, and thus exhibit differences in absolute values relative to the previous figures. These small changes have an effect

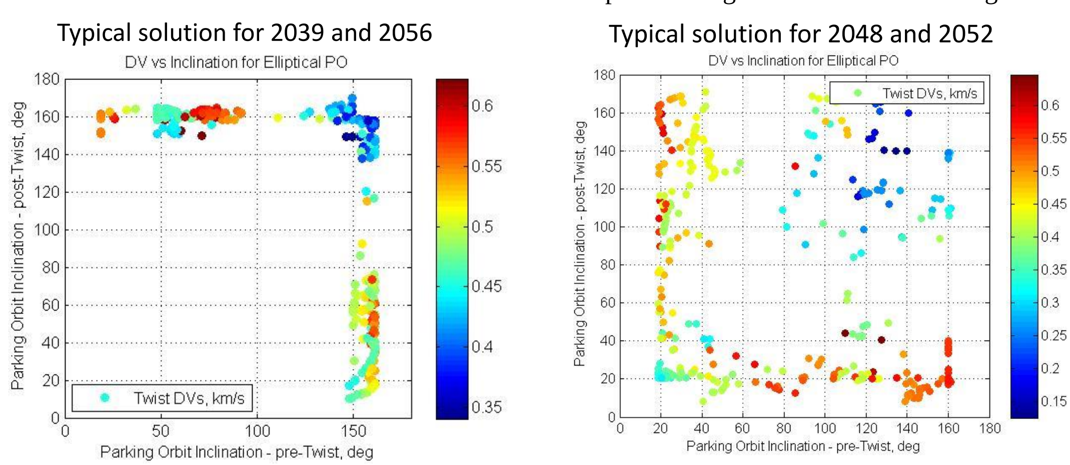


Figure 11. Late 2016 Hybrid Bi-elliptic apotwist solutions targeting 18.8 degrees North.

on the available solution space and confirm that for Hybrid trajectories the boundary conditions are sensitive to spacecraft mass changes. In all Hybrid cases for a given landing site, the bi-elliptic apotwist approach alone presents challenges for repeated site access. This can be observed in Figure 11, which illustrates application of the new latitude targeting bi-elliptic method with a set perigee location of 18.8 degrees North. For these plots the X-axis is the arrival orbit inclination and the Y-axis is the departure parking orbit inclination, and the color is the realignment ΔV. The plot on the left is typical for 2039 and 2056 solution sets with the upper right corner varying from 0.3 to 0.35 km/s; however, these solutions require highly retrograde arrival and departure parking orbits. There are some prograde departure parking orbits but they have higher realignment costs, between 0.45 and 0.5 km/s. For 2048 and 2052 (right hand plot) the solution space is different; the realignments require less ΔV but once again fall in the top right hand corner of the plot with highly retrograde arrival and departure orbits. To achieve prograde departure orbit requires a doubling of the 0.15 km/s requirement. The most challenging part of these data sets is that for 2043 there are no solutions, because the northernmost latitude based on the arrival periapsis locus, assuming a tangential co-apsidal arrival, is 14.4 degrees, which corresponds to the top edge of the locus.

D. Latitude Constrained Non-Tangential Bi-elliptic Apotwist Solutions

The lack of low ΔV solutions with low inclination departure parking orbits once again forced consideration of adding degrees of freedom to the realignment strategy in order to enable targeting latitudes that are north or south of the arrival locus while still retaining the boundary conditions for the heliocentric trajectory. The next step in the realignment method development was the implementation of a bi-elliptic apotwist targeting latitude with non-tangential arrivals. This modification to the original bi-elliptic apotwist method allows non-tangential arrival burns to be performed at locations other than the periapsis. This is the first of two steps; it allows additional freedom at Mars arrival, and is applicable for the Hybrid case where the taxi performs any additional plane change for ascent. After verifying that the method works as expected with 7 independent variables then the 9 independent variables option will be implemented to allow assessment of Hybrid and Split SEP-Chemical cases a with due east ascent constraint. The independent variables now also include hyperbolic close approach periapsis altitude and true anomaly for insertion into the initial transfer orbit, along with twist time, B-plane angles, and ascending nodes. Similar to the bi-elliptic apotwist method these solutions are found where the periapsis vectors align at the twist time for realignment and where the periapsis latitude is equal to the target latitude.

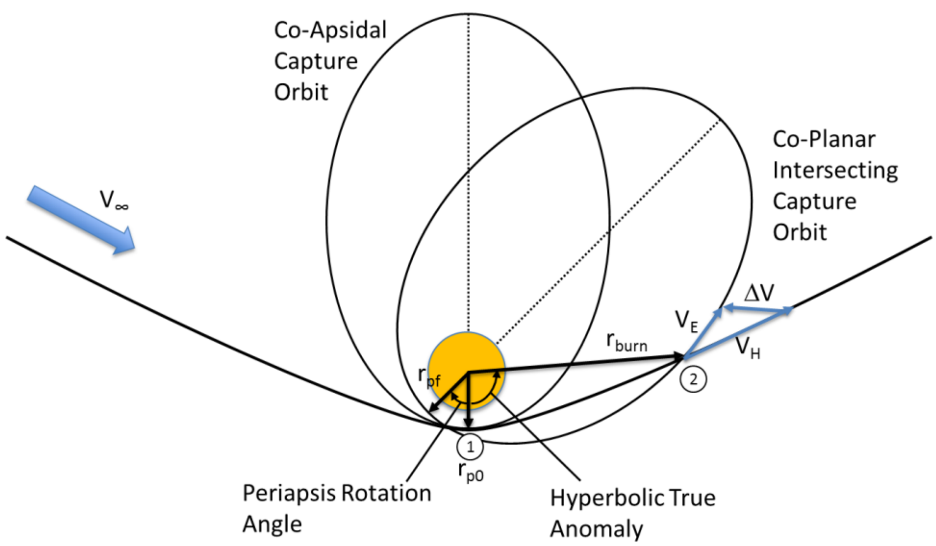


Figure 12. Non-tangential capture burn into Co-planar intersecting capture orbit.

Figure 12 illustrates this maneuver for arrival (or departure). For a nominal arrival a tangential co-apsidal burn occurs at marker one capturing the spacecraft into the co-apsidal capture orbit shown. To rotate the periapsis toward the V_∞ vector, a non-tangential burn that is coplanar with the arrival hyperbolic orbit occurs at a positive true anomaly with respect to the periapsis. This can also be done in the opposite direction (not shown) to move the periapsis away from the V_∞ vector when the insertion burn occurs before the spacecraft reaches periapsis. The method implemented to achieve this in the realignment search varies the close approach altitude and true anomaly at which the initial insertion burn occurs.

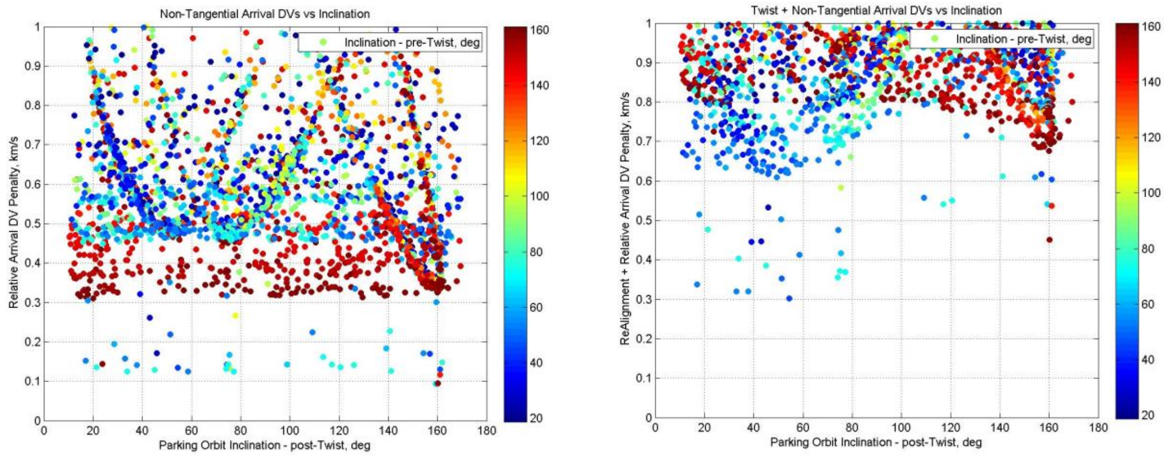


Figure 13. Late 2016 Hybrid non-tangential bi-elliptic apotwist ΔV penalty for 18.8 degrees North latitude, Jezero Crater, in 2043.

Using the bi-elliptic apotwist method there were no solutions for the 18.8 degree landing site in 2043, but with the new non-tangential arrival method there are solutions in 2043; Fig. 13 displays the 2500 solutions calculated from 5000 random initial guesses at the independent variables. On these plots the X-axis is the departure parking orbit inclination; the goal is to have this inclination be as close to the landing site latitude as possible for the lowest penalty ascent cases. The Y-axis represents ΔVs, and the color represents the arrival parking orbit inclination prior to realignment twist. The left plot is the relative arrival ΔV penalty above a tangential co-apsidal arrival, or how much more the non-tangential arrival costs for each case. The right plot is the sum of the left plot and the contribution of the twist to the realignment cost, which is the 2nd, 4th and 6th burns of the bi-elliptic transfer. The total realignment penalty for the best cases vary from 0.3 to 0.4 km/s and are greater than the total arrival or departure

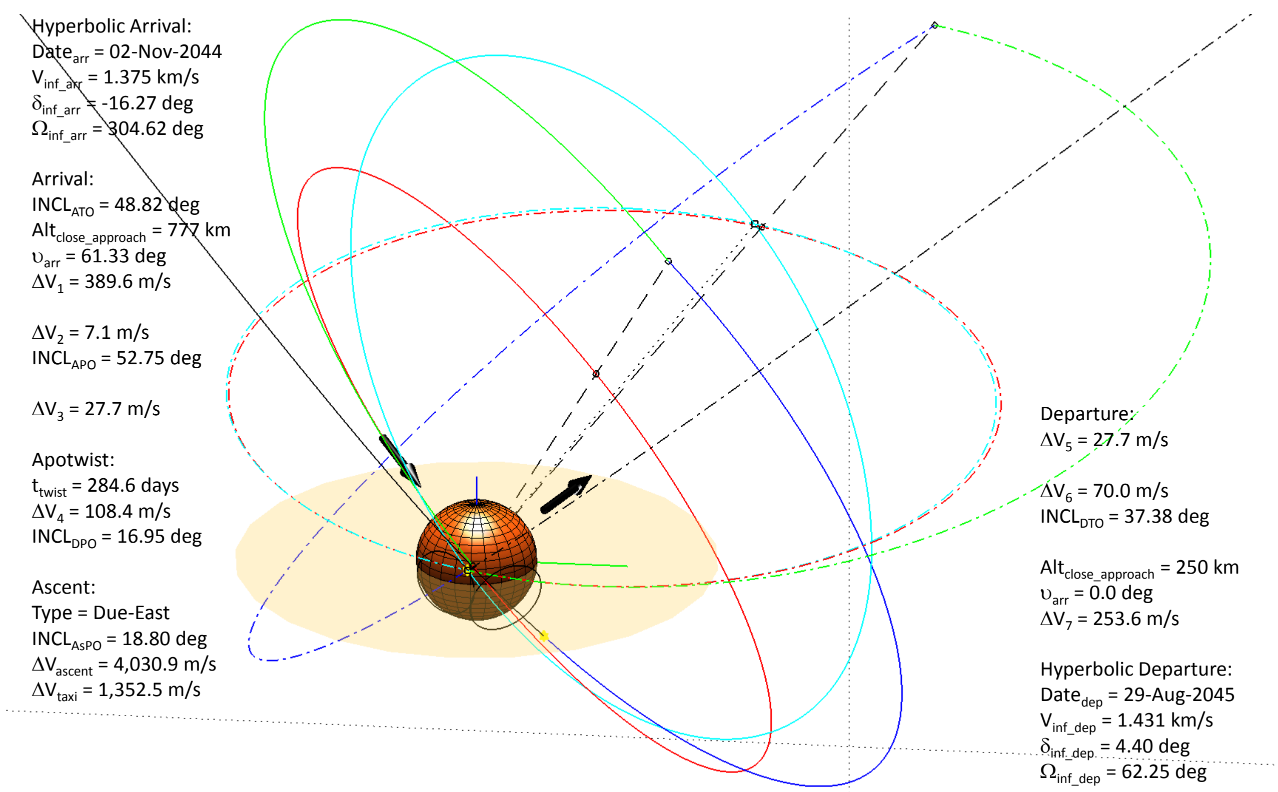


Figure 14. Late 2016 Hybrid non-tangential bi-elliptic apotwist visualization for descent to and ascent from 18.8 degrees North latitude, Jezero Crater, in 2043.

burn for the Hybrid[15]. For other opportunities where bi-elliptic solutions exist with tangential arrival, this strategy allows solutions with a reduced total realignment ΔV. This updated method was run for opportunities of interest in the 2040s and 2050s. Plots of the 500 lowest DV cost solutions for these opportunities can be found in Appendix D. Figure 14 is a plot of one of the favorable 2043 solutions with < 0.35 km/s total reorientation requirement and a post-twist parking orbit directly over the landing site. This solution allows for landing at Jezero Crater and due East ascent to the heliocentric in-space transportation system that is aligned for Mars departure. In the figure, the locus for arrival and departure are plotted on Mars and the small yellow star that separates the black hyperbolic arrival trajectory and the blue transfer orbit depicts the location of the non-tangential arrival burn.

E. Hybrid Architecture Latitude Sensitivity

Jezero Crater is one of many identified sites of interest on Mars. An initial sensitivity assessment was performed using the latitude targeted non-tangential realignment approach to understand sensitivity of landing site to realignment cost and solution availability. Initially two additional sites were chosen, Simonies Cavus at 33.5 degrees North and Protonilus Mensae at 42 degrees North. For Simonies Cavus, even with the non-tangential arrivals there were no solutions in 2048, and only 2052 yielded reasonable realignment performance. In 2056 the best solution was nearly 1 km/s. Similarly for Protonilus Mensae no solutions were found for 2039, 2043, 2048, or 2056, and only 2052 yielded solutions, but with a ΔV greater than 0.2 km/s. Further investigation was necessary and a smaller set of 100 initial guesses was made for latitudes from 18.8 degrees up to 35 degrees. As latitude increases fewer and fewer solutions are found; in addition as the latitude moves further North the mean altitude at which the non-tangential arrival burn occurs increases rapidly and with it the corresponding ΔV penalty. It is clear that there is a limit to the amount of perigee change that can be done by the non-tangential arrival before it becomes prohibitively expensive. This behavior observed for northern latitudes is due to the size and location of the Mars arrival focus. The implemented realignment methods do not allow access to sites that are well beyond the range of latitudes encompassed by the arrival focus. Arrival focus size and vertical orientation is plotted in Fig 15. for both the Hybrid and Split SEP-Chemical architectures. The size of the locus of perigee vectors is a function of the magnitude of the arrival V_∞. For piloted Hybrid arrivals are between a V_∞ of 0.7 and 1.4 km/s and for the minimum energy chemical piloted trajectories for the Split SEP-Chemical architecture the V_∞ is between 2.6 and 4.8 km/s leading to larger locus and larger potential range of accessible destinations.

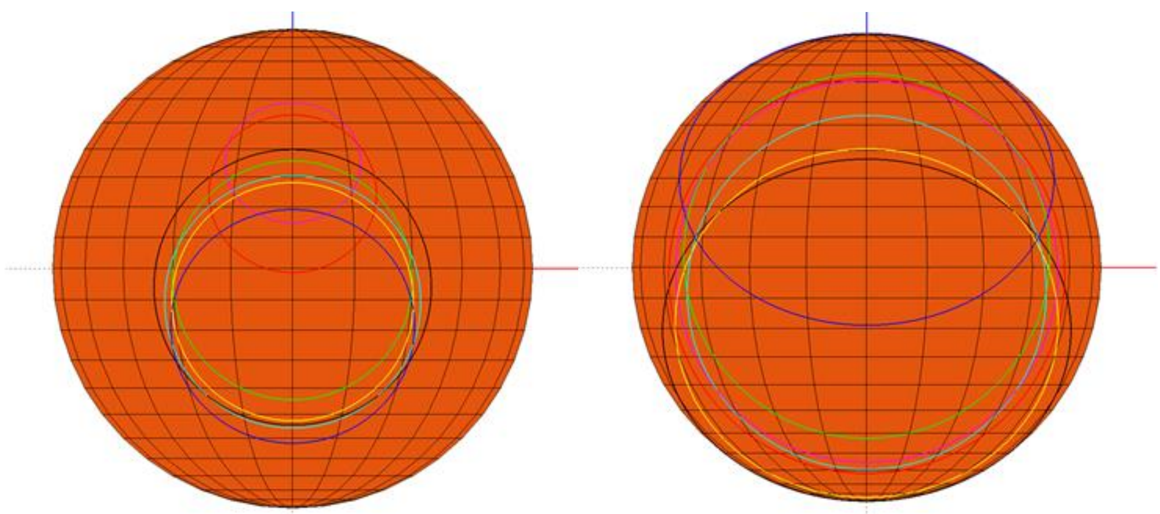
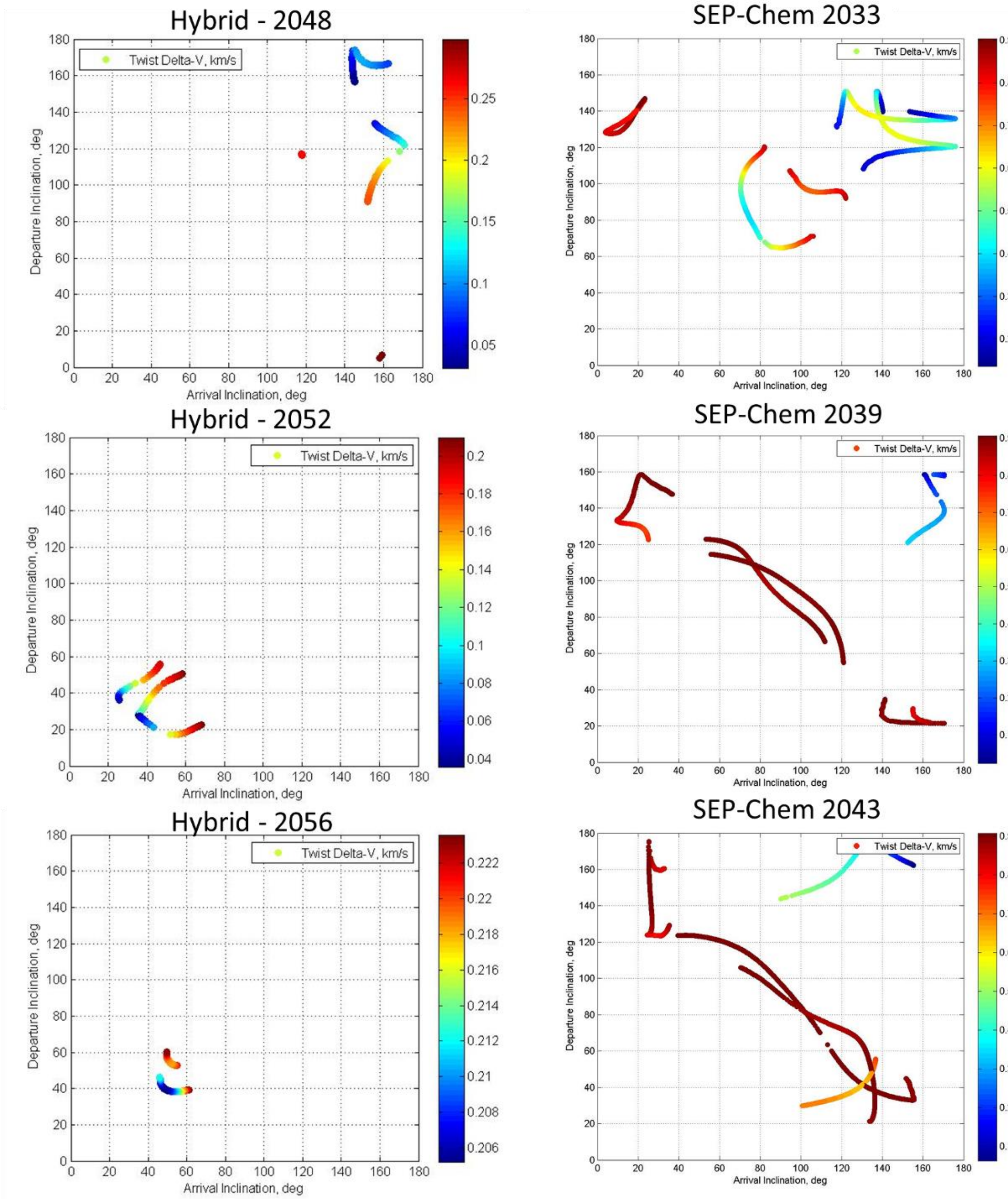


Figure 15. Hybrid and Split SEP-Chemical piloted Mars arrival locus of arrival perigee vectors.

VI. Conclusions and Next Steps

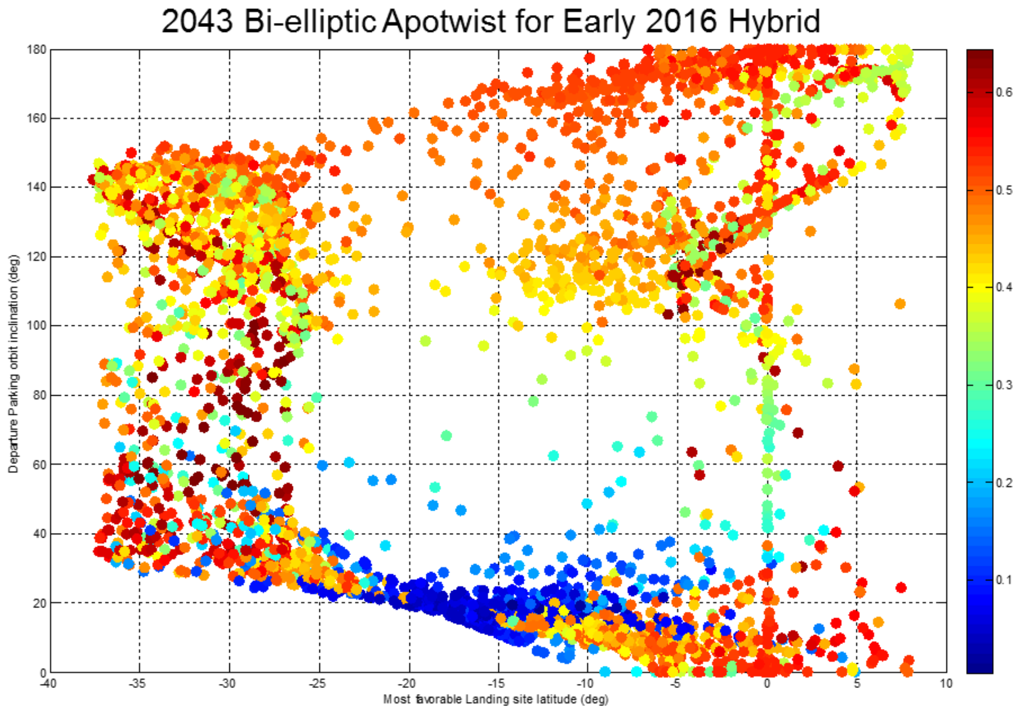
The ongoing method and capability development for Mars SOI assessment is a first step towards optimizing in-space transportation mission design for EMC architectures. Realignment of piloted Mars transportation systems from arrival to departure parking orbit can be accomplished across multiple opportunities for both Hybrid and Split SEP-Chemical architectures for the relatively small ΔV of 0.15 km/s with a bi-elliptic apotwist and 10-sol transfer orbits. However constraints imposed by destination mission transportation limit reorientation solution options. Parking orbits with line of nodes near the equatorial plane and low inclination enable lowest cost round Phobos and/or Deimos taxi ΔV. The Hybrid concept in the 2030s using a butterfly for short expeditions or a bi-elliptic apotwist for long expeditions requires a round trip taxi ΔV for Phobos or Deimos of 2 - 2.25 km/s and for Phobos and Deimos tours 2.5 – 2.75 km/s is required. The EMC lander concept requires the Mars arrival parking orbit to have a perigee directly over the landing site latitude. Initial latitude targeted assessments were completed for the Jezero crater region of Mars with the Hybrid option. Very few low ΔV solutions were found with prograde departure inclinations, and some opportunities were infeasible. By adding non-tangential arrival burn flexibility more solutions were found, but in-space transportation reorientation costs are still high for some opportunities. After assessment of sensitivity to latitude it is clear that the current methods implemented do not enable access to a broad enough range of surface latitudes across all opportunities with the existing EMC EDL constraints and Hybrid in-space transportation system concept. This assessment shows that with the methods described, the total cost of Mars SOI realignment for fixed landing sites can be larger than either Mars arrival or departure burns for optimized heliocentric Hybrid trajectories. Increasing the number of independent variables by allowing non-tangential departures has shown the potential for small improvements beyond what is presented here and is required for cases where the ascent stage is limited to due east ascent. The next step for Mars SOI assessment is expanding the boundary conditions beyond Mars SOI to include arrival and departure V_∞ to enable investigation of solutions that include varied locus size. In addition the arrival and departure declinations and the apoapsis altitude of the parking orbit are being considered to help further optimize global solution sets for the EMC. Changing the EDL and ascent constraints also shows significant promise and should be investigated to enable increased operational flexibility at Mars. Only after penalties for accessibility to sites of interest on Mars is quantified can transportation and lander architecture options be compared fairly.

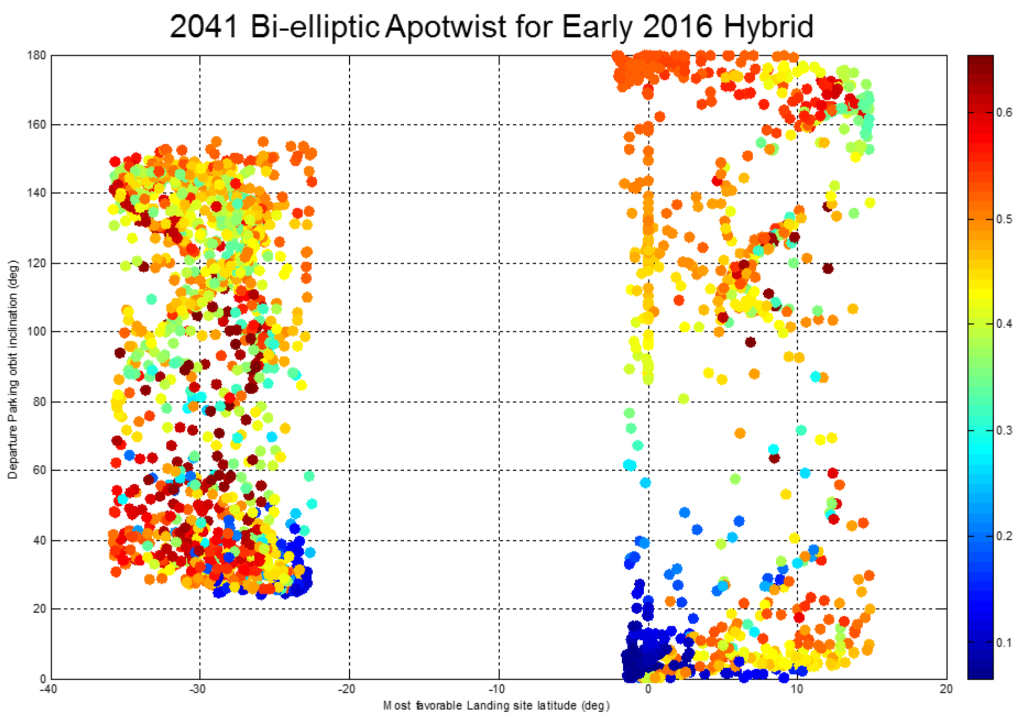
Appendix A. Selected Early 2016 Hybrid and Split SEP-Chemical Apotwist Solutions Sets

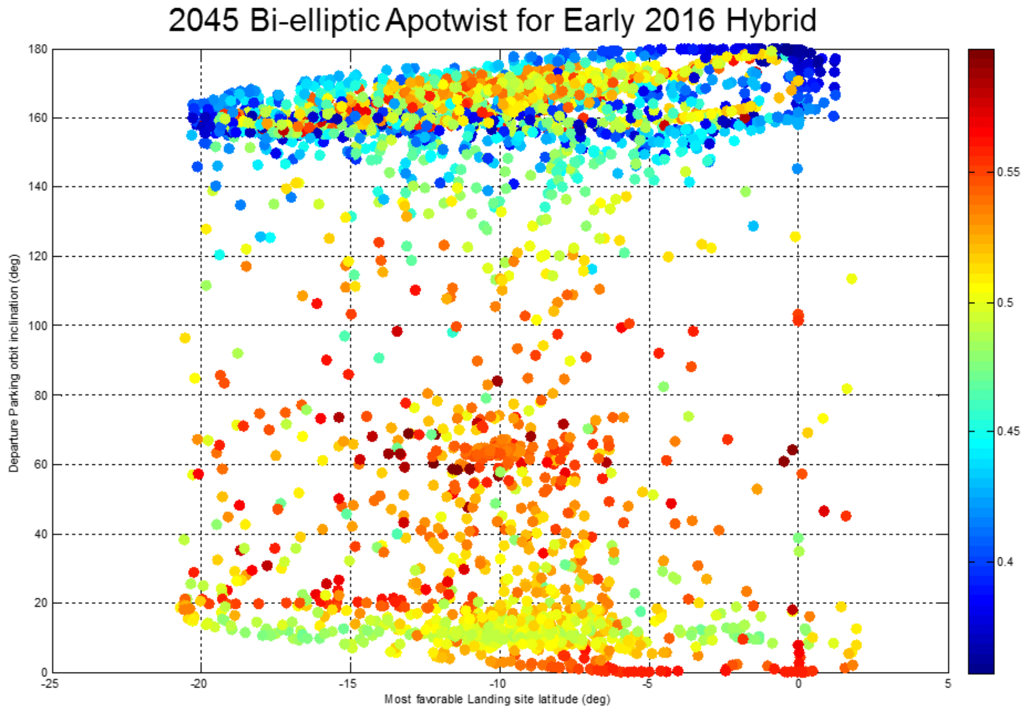


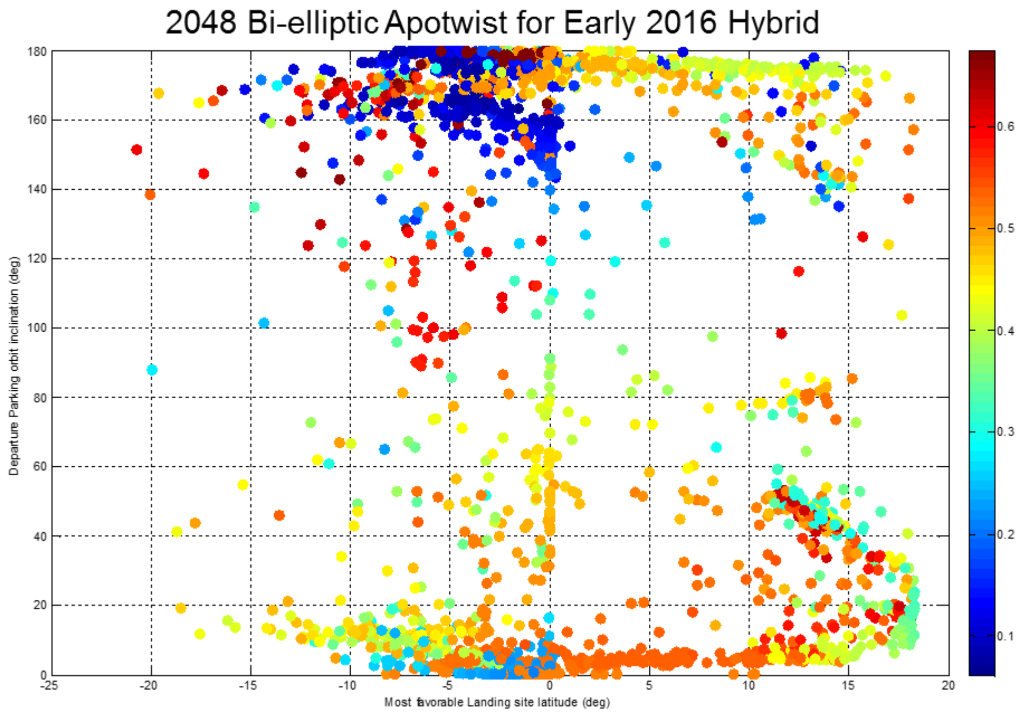
Appendix B. Hybrid Bi-elliptic Apotwist for Long Stay Phobos and/or Deimos Access

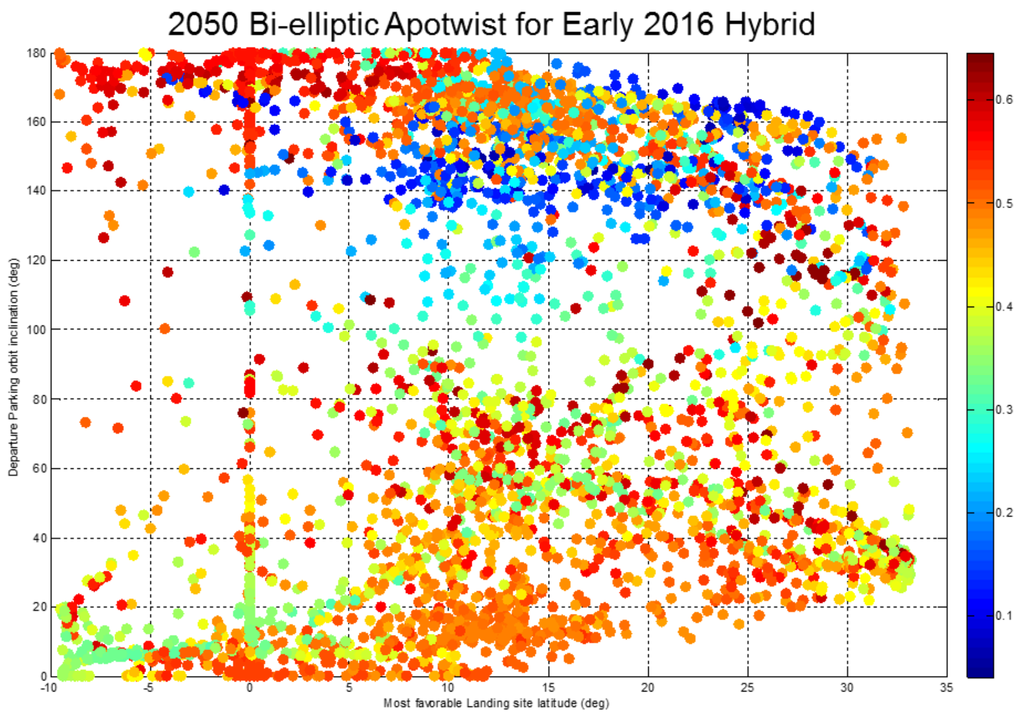
Appendix C. Hybrid Bi-elliptic Apotwist for Surface Access

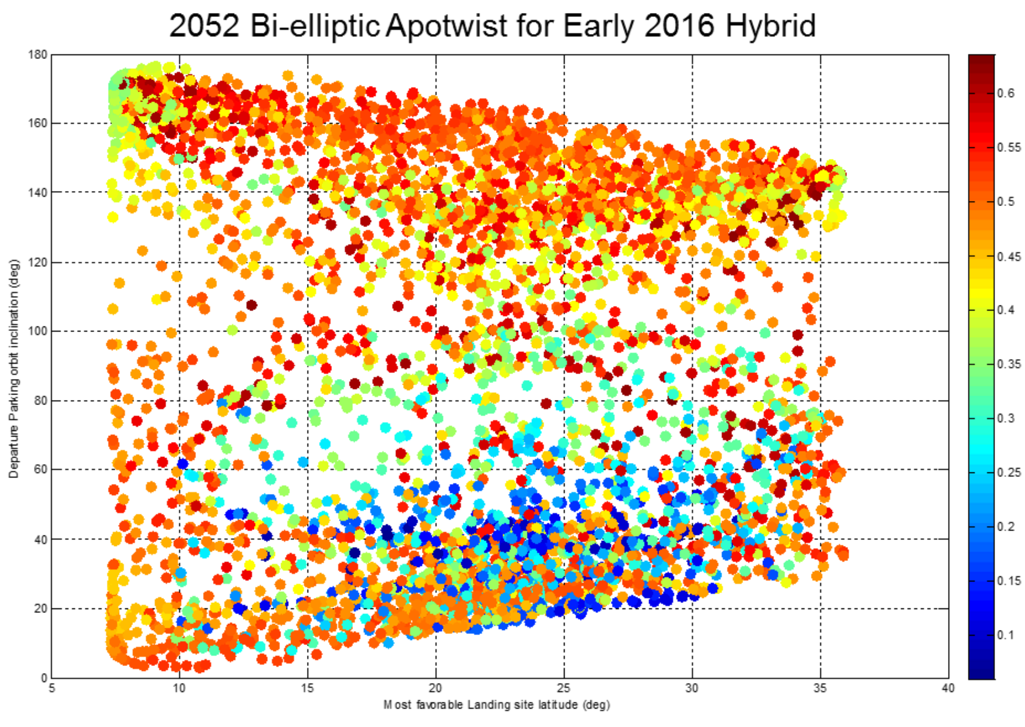




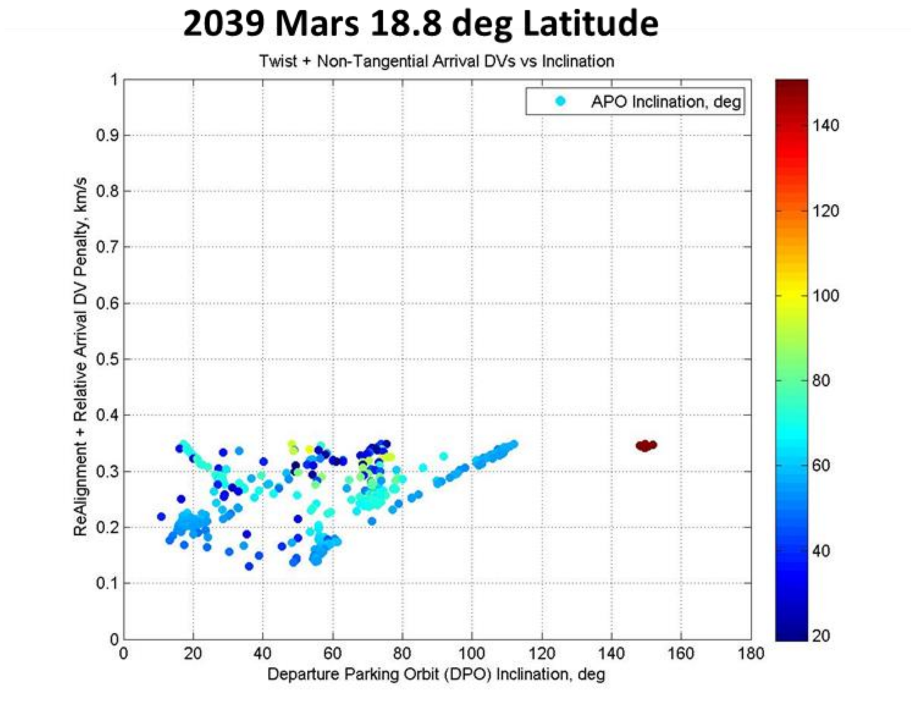

2045 Bi-elliptic Apotwist for Early 2016 Hybrid
Departure Parking orbit inclination (deg)
Most favorable Landing site latitude (deg)

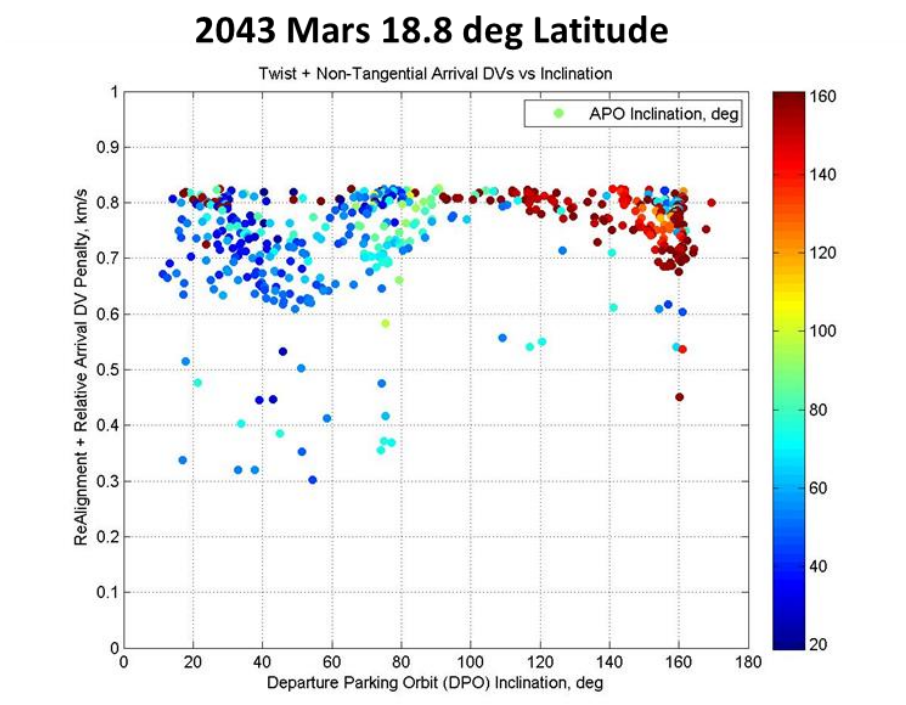

2048 Bi-elliptic Apotwist for Early 2016 Hybrid
Departure Parking orbit inclination (deg)
Most favorable Landing site latitude (deg)


2050 Bi-elliptic Apotwist for Early 2016 Hybrid
Departure Parking orbit inclination (deg)
Most favorable Landing site latitude (deg)

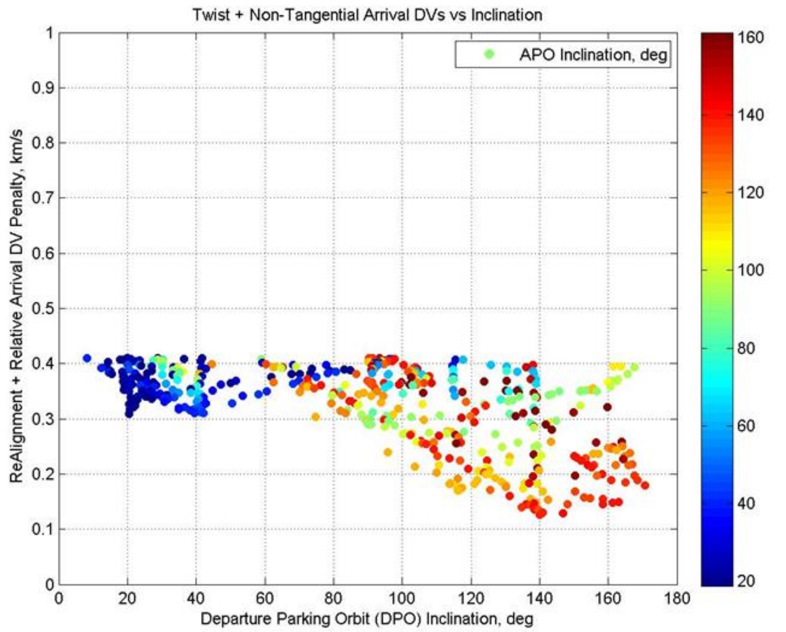

2052 Bi-elliptic Apotwist for Early 2016 Hybrid
Departure Parking orbit inclination (deg)
Most favorable Landing site latitude (deg)

Appendix C. Late 2016 Hybrid non-tangential bi-elliptic apotwist lowest 500 ΔV penalty solutions for 18.8 degrees North latitude, Jezero Crater.

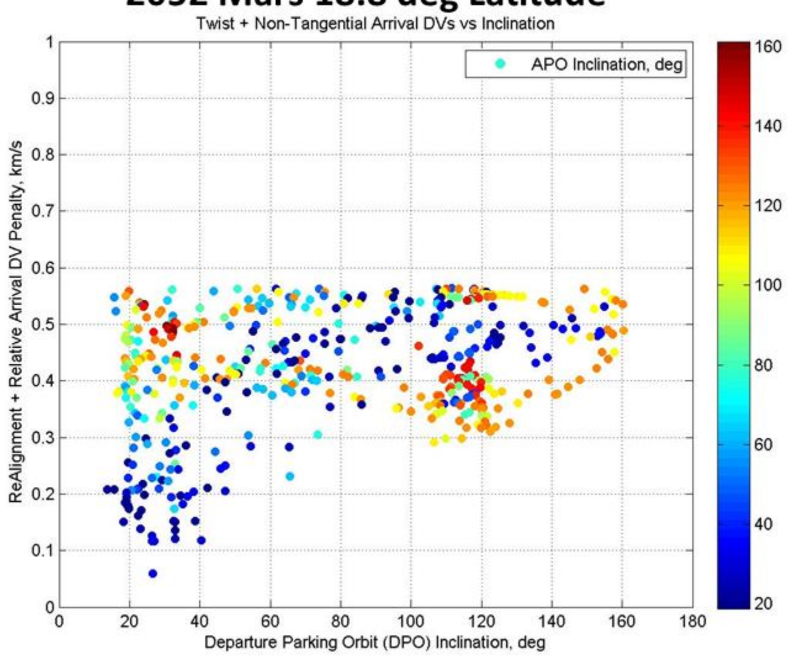


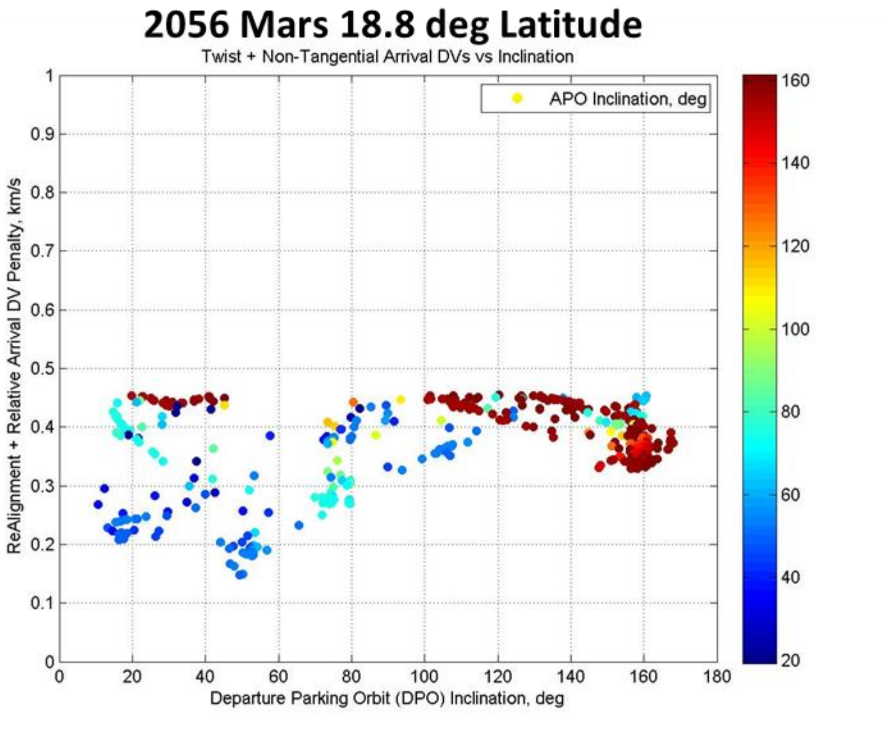


2048 Mars 18.8 deg Latitude



2052 Mars 18.8 deg Latitude





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