ESCAPE, PLASMA AND ACCELERATION DYNAMICS EXPLORERS (ESCAPADE) MISSION DESIGN

Jeffrey S. Parker,[1] Connor Ott,[2] Andrew Koehler,[†] Sandeep Baskar,[†] Mitchell Rosen,[†] and Timothy Sullivan[†]

The Escape, Plasma and Acceleration Dynamics Explorers (ESCAPADE) mission will provide a comprehensive picture of how solar wind energy flows through Mars' unique hybrid magnetosphere to drive ion and sputtering escape. This paper provides a new examination into ESCAPADE's mission design, as of 2022, surveying each phase of the transfer from launch through the end of the primary science mission at Mars. The two ESCAPADE spacecraft launch as secondaries on a launch in 2024 and traverse a complex mission design to arrive into the same science orbit about Mars, establishing the first formation in orbit about Mars. ESCAPADE's science includes two campaigns: the first involves both spacecraft being in the same orbit in a string-of-pearls configuration; the second involves both spacecraft traversing very different plasma regions about Mars.

INTRODUCTION

The Escape, Plasma and Acceleration Dynamics Explorers (ESCAPADE) mission is supported by NASA's Science Mission Directorate (SMD) within an opportunity under the Small Innovative Missions for Planetary Exploration (SIMPLEx) program. The ESCAPADE mission includes two identical spacecraft, *Blue* and *Gold*, whose maximum expected mass are each 396 kg presently. They will each enter the same elliptical orbit about Mars, collecting in situ atmospheric data in formation over six months. The spacecraft will then transition to different science orbits and collect spatially different, simultaneous observations of the atmosphere over the next five months, with opportunities for extensions. This paper describes the mission design that enables two spacecraft to launch via a low-cost rideshare launch, transfer to Mars, and establish the Martian formation. The ESCAPADE mission design has been described in the past with variations in launch as a rideshare aboard Psyche;[3,4,5] that launch opportunity shifted beyond ESCAPADE's capabilities and a substantial change has been implemented. The two spacecraft are now built by

---

[1] Chief Technology Officer, Advanced Space, 1400 W 122nd Ave Suite 200, Westminster CO 80234.

[2] Astrodynamicist, Advanced Space, 1400 W 122nd Ave Suite 200, Westminster CO 80234.

[3] Parker, J. S., Parrish, N. L., Lillis, R., Curry, S., & Curtis, C., "Escape, Plasma and Acceleration Dynamics Explorers (ESCAPADE)," *43rd AAS Guidance and Control Conference*, Paper AAS 20-102, Breckenridge, CO, 1-5 February 2020.

[4] Parker, J. S., Parrish, N., Lillis, R., Curry, S., Curtis, D., Luhmann, J., Puig-Suari, J., Russell, C., & Brain, D., "Mars Ion and Sputtering Escape Network (MISEN) Mission Concept," *2018 Astrodynamics Specialist Conference*, Paper AAS 18-423, Snowbird, Utah, 19-23 August 2018.

[5] Parker, J.S., Parrish, N., Sullivan, R., Lillis, R., Curry, S., & Curtis, D., "Escape, Plasma, and Acceleration Dynamics Explorers (ESCAPADE) Mission Design," AAS 20-602, *AAS AIAA Astrodynamics Specialist Conference*, South Lake Tahoe, CA, August 9-13, 2020.

Rocket Lab with very different capabilities from previous descriptions. The spacecraft propulsion is now all-chemical and substantial enough to support rideshare opportunities to Mars, starting from orbits such as Sun Synchronous. The resulting mission design arrives at Mars relatively quickly, and descends far quicker than previous designs; ultimately providing the opportunity to start science April 1, 2026, several months sooner than previous designs.

Scientific Background

Atmospheric Escape at Mars

The scientific exploration that ESCAPADE will provide has not changed since previous descriptions[1,2,3] and will be rephrased here. ESCAPADE enhances and supplements the investigations conducted by the Mars Atmosphere Volatile and EvolutioN (MAVEN) mission for a small fraction of MAVEN's cost. The MAVEN mission was designed to characterize atmospheric escape and its dependence on solar energetic drivers, and hence to enable reliable estimates of atmospheric escape over Martian history.[6] MAVEN measures escape through four primary channels or processes.[7]

Two of the escape processes, photochemical escape[8,9] of O, C and N and Jeans escape[10,11] of H, are driven mostly by solar extreme ultraviolet (EUV) and Martian season (including dust activity). They can be constrained with remote sensing measurements and are reasonably symmetric with respect to solar zenith angle.[12,13,14,15] MAVEN is continuing to characterize these processes[11,16].

[6] Jakosky, B. M., et al. (2015), The Mars Atmosphere and Volatile Evolution (MAVEN) Mission, *Space Science Reviews*, 1-46, doi:10.1007/s11214-015-0139-x.

[7] Lillis, R. J., et al. (2015), Characterizing Atmospheric Escape from Mars Today and Through Time, with MAVEN, *Space Science Reviews*, 1-66, doi:10.1007/s11214-015-0165-8.

[8] Fox, J. L., and F. Bakalian (2001), Photochemical escape of atomic carbon from Mars, *Journal of Geophysical Research-Space Physics*, *106*(A12), 28785-28795, doi:10.1029/2001JA000108.

[9] Groller, H., H. Lichtenegger, H. Lammer, and V. I. Shematovich (2014), Hot oxygen and carbon escape from the martian atmosphere, *Planetary and Space Science*, *98*, 93-105.

[10] Chaffin, M. S., C. J.-Y., I. Stewart, M. Montmessin, and N. Schneider (2014), Time Variability of Martian Hydrogen Escape, *Geophysical Research Letters*, doi:10.1002/2013GL058578.

[11] Clarke, J. T., J.-L. Bertaux, J.-Y. Chaufray, G. R. Gladstone, E. Quemerais, J. K. Wilson, and D. Bhattacharyya (2014), A Rapid Collapse of the Hydrogen Corona of Mars, *Geophysical Research Letters*, doi:10.1002/2014GL061803.

[12] Chaffin, M. S., et al. (2015), Three-dimensional structure in the Mars H corona revealed by IUVS on MAVEN, *Geophysical Research Letters*, *42*(21), 9001-9008, doi:10.1002/2015gl065287.

[13] Deighan, J., et al. (2015), MAVEN IUVS observation of the hot oxygen corona at Mars, *Geophysical Research Letters*, *42*(21), 9009-9014, doi:10.1002/2015GL065487.

[14] Lee, Y., M. R. Combi, V. Tenishev, S. W. Bougher, and R. J. Lillis (2015), Hot oxygen corona at Mars and the photochemical escape of oxygen: Improved description of the thermosphere, ionosphere, and exosphere, *Journal of Geophysical Research: Planets*, *120*(11), 1880-1892, doi:10.1002/2015JE004890.

[15] Lillis, R. J., et al. (2017), Photochemical escape of oxygen from Mars: First results from MAVEN in situ data, *Journal of Geophysical Research-Space Physics*, *122*(3), 3815-3836, doi:10.1002/2016ja023525.

[16] Rahmati, A., et al. (2017), MAVEN measured oxygen and hydrogen pickup ions: probing the Martian atmosphere and neutral escape, *Journal of Geophysical Research*, Space Physics, doi:10.1002/2016JA023371.

In contrast, the other two processes (which ESCAPADE addresses), are governed mostly by the motion of ions in near-Mars space, and hence by the global patterns of electric and magnetic fields resulting from the interaction of Mars' upper atmosphere and ionosphere with the highly variable solar wind and interplanetary magnetic field (IMF),[17,18] as shown in Figure 1. These processes are a) **ion escape**, where neutrals from the thermosphere or exosphere are ionized, then energized and accelerated away from Mars by these fields,[19] and b) **sputtering (or sputtered) escape**, where neutrals are ionized but then accelerated back into the atmosphere, giving sufficient energy to thermospheric (< 200 km) neutrals to allow them to escape, essentially 'splashing' them out.[20] As the sputtered neutrals cannot be directly detected by any existing instrument, straightforward calculations (based on detailed simulations) are used to convert precipitating ion spectra into sputtered escape rates.[21] Both processes have complex global structure,[22] are dependent on EUV,[23] and vary significantly with solar wind density and velocity and the strength and direction of the IMF.[24,25]

Figure SEQ Figure * ARABIC 1. Simulation of ion escape from Mars. Yellow, magenta and blue arrows represent solar wind velocity, IMF direction and convection electric field respectively. Colors represent log energy, increasing from blue to red.

[17] Brain, D. A., D. Hurley, and M. R. Combi (2010), The solar wind interaction with Mars: Recent progress and future directions, *Icarus*, *206*(1), 1-4, doi:10.1016/j.icarus.2009.10.020.

[18] Curry, S. M., J. Luhmann, Y. Ma, M. Liemohn, C. Dong, and T. Hara (2015), Comparative pick-up ion distributions at Mars and Venus: Consequences for atmospheric deposition and escape, *Planetary and Space Science*, *115*, 35-47, doi:http://dx.doi.org/10.1016/j.pss.2015.03.026.

[19] Lundin, R., S. Barabash, A. Fedorov, M. Holmstrom, H. Nilsson, J. A. Sauvaud, and M. Yamauchi (2008), Solar forcing and planetary ion escape from Mars, *Geophysical Research Letters*, *35*(9).

[20] Luhmann, J. G., and J. U. Kozyra (1991), Dayside pickup oxygen ion precipitation at Venus and Mars: Spatial distributions, energy deposition and consequences, *Journal of Geophysical Research: Space Physics*, *96*(A4), 5457-5467, doi:10.1029/90JA01753.

[21] Wang, Y.-C., J. G. Luhmann, F. Leblanc, X. Fang, R. E. Johnson, Y. Ma, W.-H. Ip, and L. Li (2014), Modeling of the O+ pickup ion sputtering efficiency dependence on solar wind conditions for the Martian atmosphere, *Journal of Geophysical Research*.

[22] Curry, S. M., M. Liemohn, X. Fang, Y. Ma, and J. Espley (2013), The influence of production mechanisms on pick-up ion loss at Mars, *Journal of Geophysical Research-Space Physics*, *118*(1), 554-569, doi:Doi 10.1029/2012ja017665.

[23] Dubinin, E., et al. (2017), Effects of solar irradiance on the upper ionosphere and oxygen ion escape at Mars: MAVEN observations, *Journal of Geophysical Research-Space Physics*, *122*(7), 7142-7152, doi:10.1002/2017ja024126.

[24] Lundin, R., S. Barabash, M. Holmstrom, H. Nilsson, Y. Futaana, R. Ramstad, M. Yamauchi, E. Dubinin, and M. Fraenz (2013), Solar cycle effects on the ion escape from Mars, *Geophysical Research Letters*, *40*(23), 6028-6032.

[25] Ramstad, R., S. Barabash, Y. Futaana, H. Nilsson, X.-D. Wang, and M. Holmström (2015), The Martian atmospheric ion escape rate dependence on solar wind and solar EUV conditions: 1. Seven years of Mars Express observations, *Journal of Geophysical Research: Planets*, *120*(7), 1298-1309, doi:10.1002/2015JE004816.

Mission Team

The ESCAPADE leadership is located at the University of California Berkeley, including the Principal Investigator, Lead Scientist, Program Manager, and Systems Engineering team. Mission design is provided by Advanced Space. The navigation will be performed by UC Berkeley and Advanced Space. The spacecraft buses are Photon buses with Mars modifications, constructed and integrated by Rocket Lab. The ground tracking network and communications are conducted by the Deep Space Network (DSN).

Mission Design

The objective of the ESCAPADE mission design is to transfer the two spacecraft from their launch, which is baselined presently to be a Sun Synchronous Orbit rideshare, to a formation in orbit about Mars. The initial scientific orbit is an elliptical orbit with a periapse in the upper atmosphere of Mars, approximately 160 km altitude, an apoapse altitude of 8400 km, and an inclination of 65 degrees. The two spacecraft will form a string-of-pearls formation with a leader-follow duration that oscillates between 5 and 30 minutes, sampling the same region of Martian environment at different temporal separations. The two spacecraft must cooperate throughout the mission and yet never endanger each other from an impact or other interference. This mission design is very complex and will be described here.

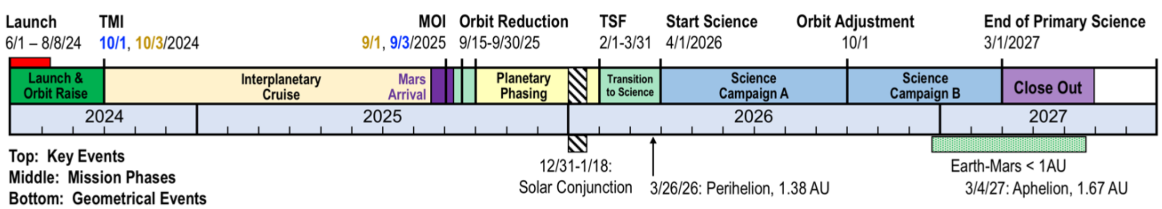


Figure 2. ESCAPADE's baseline mission timeline, showing the launch period for a Sun Synchronous rideshare through the end of Primary Science at Mars.

The ESCAPADE mission has seven phases with several key events as illustrated in Figure 2. These phases are introduced here with details in the sections to follow.

1. **Launch and Orbit Raise**. The first phase is the Launch and Orbit Raise Phase, which is designed to systematically raise both spacecraft orbits such that the *Blue* spacecraft performs its Trans-Mars Injection (TMI) maneuver to depart Earth on October 1, 2024 and the *Gold* spacecraft performs its TMI 48 hours later on October 3, 2024. NASA is selecting a launch for ESCAPADE presently, which may be a rideshare from many different orbits or even a direct-to-Mars. Assuming an Earth orbit rideshare, each of the two ESCAPADE spacecraft will conduct a series of maneuvers to raise the orbit and change the plane to target the proper Trans-Mars Injection (TMI) conditions and depart Earth.
2. **Interplanetary Cruise**. The two spacecraft traverse Type II transfers to Mars. One third of the way through the interplanetary cruise, the two spacecraft are close enough in the sky to permit MSPA (multiple spacecraft per aperture) with the Deep Space Network (DSN), and the two spacecraft continue to benefit from MSPA for the remainder of the mission. This feature helps reduce operational costs of communicating with two spacecraft at Mars.

3. **MOI**. MOI-G (*Gold*'s Mars Orbit Insertion maneuver) is nominally conducted on 9/1/2025 and MOI-B follows 48 hours later. This order of MOI maneuvers reduces the interplanetary cruise maneuver cost needed to establish MSPA earlier in the mission. The MOI maneuvers are each inertially fixed maneuvers and each target capture orbits with orbital periods of ~87 hours each.
4. **Orbit Reduction**. The two spacecraft each reduce their apoapse and periapse to remove orbit insertion errors and enter safe orbits about Mars. This phase extends through a four-month quiescent period during which the planets phase prior to initiating the science investigation. ESCAPADE also coasts through solar conjunction during this time period in a safe and stable orbit.
5. **Transition to Science Formation**. Each spacecraft performs four maneuvers in a choreographed fashion to reduce its orbit and to target the science formation without incurring any close approaches between the spacecraft and between the Martian moons.
6. **Primary Science**. The ESCAPADE mission conducts an 11-month primary science phase, including six months in Campaign A and five months in Campaign B.
    - **Science Campaign A**. The two spacecraft orbit Mars in approximately the same orbit in order to measure time-varying properties of the same regions of space about the planet. The duration within which one spacecraft chases the other oscillates between 5 and 30 min.
    - **Orbit Adjustment**. The two spacecraft change their apoapse altitudes: one rising and one falling to establish the Science Campaign B.
    - **Science Campaign B**. The two spacecraft orbit Mars in different orbits with different precession profiles in order to measure spatially-varying properties of the space about the planet.
7. **Decommissioning**. The spacecraft conduct operations to conclude the mission and dispose of the spacecraft.

Details of each phase are provided in the sections below.

Spacecraft Modeling

The details of the spacecraft are outside of the scope of this paper, except to describe several key elements. First, the spacecraft bus is a modified Photon bus, constructed and integrated at Rocket Lab. The wet mass of each spacecraft as modeled here is 396 kg each, including a maximum expected dry mass of 140 kg, 244 kg of propellant, and 12 kg of cold nitrogen gas. The main propulsion system is the Hyper Curie system, which is a restartable bi-propellant system using electric pumps to supply pressurized propellant to a thrust vector-controlled engine. The nitrogen is used for desaturation maneuvers, small translational maneuvers, and other system adjustments. The analysis presented here uses low estimates for the thrust and efficiency of each system. The main engine is modeled here with a thrust of 471 N and Isp of 295 sec; the nitrogen translational maneuvers are modeled with a thrust of 3.2 N and Isp of 70 sec. The main engine is qualified to 18 restarts and ESCAPADE benefits with each and every one of those planned thruster firings.

Launch and Orbit Raise Phase

The Launch and Orbit Raise (LOR) Phase includes the launch, commissioning of the vehicles, and any/all maneuvers needed to depart Earth onto the interplanetary cruise.

Launch

ESCAPADE has established a very flexible posture for rideshares to launch. The mission may be launched in any of four rideshare configurations, including (1) Direct-to-Mars rideshares, (2) Sun Synchronous Orbit rideshares with an additional boost, (3) General Earth orbit rideshares with a potential boost, and (4) other rideshare opportunities, such as lunar flybys.

To support many potential launch opportunities, ESCAPADE has opted to design towards a general-purpose orbit raise and plane change strategy to achieve desired interplanetary trajectory targets from many different starting orbits. This strategy expects the primary mission be launched into an Earth orbit prior to August 15, 2024 within a specified range of orbit orientations and sizes. Additionally, the design assumes the launch vehicle can boost both ESCAPADE spacecraft into a large orbit with period greater than or equal to 1.6 days. The orbit raise strategy includes several revolutions in large Earth orbits (between 3-day and 10-day periods) which culminates in one large (25-day or higher orbit) in which necessary plane change adjustments are made to align the spacecraft trajectory with outbound targets. Finally, the spacecraft perform their trans-Mars injection burn (TMI) to depart Earth and begin the interplanetary trajectory.

Spacecraft Checkout

The ESCAPADE mission expects that the spacecraft checkout will be very quick, given that the Photon bus is designed to be the upper stage of a launch vehicle. The mission plan calls for one spacecraft to execute its first burn 4-5 days after launch and the other spacecraft to follow ~2 days later. Every scenario permits many more days in case the checkout discovers an off-nominal condition on one or both of the spacecraft.

The reference mission places both spacecraft in a 1.6-day orbit about the Earth. The *Blue* spacecraft executes its first orbit raise maneuver after three revolutions, approximately 4.8 days after launch. The *Gold* spacecraft follows on the next revolution, approximately 6.4 days after launch. Either may be delayed up to six days if needed and be considered nominal.

Orbit Raise

The orbit raise component of the reference mission serves several important purposes. The foremost reason is to increase the spacecraft orbit sizes to accommodate large changes in plane and to decrease the necessary ΔV required to execute the TMI burn. Additionally, the orbit raise provides a means of phasing the spacecraft such that they execute TMI on the correct dates given a variable injection date from the launch vehicle. Finally, spending time in larger orbits incurs fewer passages through Earth's Van Allen belts.

Plane Change

It is crucial that the spacecraft arrive at their TMI dates with proper orbit orientation so that the TMI burns are as efficient as possible. To allow this, the final, largest orbit in the sequence between launch and TMI is very large, with apogee altitude greater than 1 million kilometers. This allows for very efficient plane changes near apogee. This final orbit can look very different depending on the orientation of the initial orbit. However, in general the plane change maneuvers taking place near apogee of the final orbit cost between 0 and 100 m/s.

Trans-Mars Injection

The TMI maneuvers are designed to be approximately centered about perigee and boost the velocities of each spacecraft by approximately 600 m/s, depending on the launch scenario. They are inertially-fixed maneuvers and target the hyperbolic state vectors summarized in Table 1. These vectors are represented in the Earth-centered EME2000 coordinate frame. The time of day of each TMI will be updated with DSN involvement as ESCAPADE gets closer to launch, with the expectation that the time of day will permit a rapid acquisition by the DSN shortly after the maneuver.

Table 1: ESCAPADE post-TMI targeted States

Parameter	Blue	Gold
Epoch	01-OCT-2024 12:00:00.000 ET	03-OCT-2024 12:00:00.000 ET
V_∞, km/s	3.34498	3.34464
Right Ascension of the Launch Asymptote, deg	102.885	102.332
Declination of the Launch Asymptote, deg	16.367	16.482
Clock Angle, deg	-100.955	-100.807
Radius of Periapse, km	7000	7000
True Anomaly, deg	30	30

Interplanetary Cruise Phase

The interplanetary cruise phase begins after both spacecraft have executed their TMI maneuvers and are on hyperbolic escapes from the Earth. The *Blue* spacecraft performs TMI first (TMI-B), but arrives at Mars second, creating trajectories such that the MSPA constraint and Mars B-Plane targets are satisfied for a low total trajectory correction maneuver (TCM) budget.

Interplanetary Cruise with Multiple Spacecraft Per Aperture

Figure 2 illustrates ESCAPADE's interplanetary cruise. The two spacecraft depart Earth on the left-hand side and arrive at Mars on the right-hand side of the figure. The end of the white segment indicates the point at which MSPA is satisfied for the rest of the flight until Mars. Blue and yellow Delta-V lines are shown proportional to the size of each deterministic maneuver.

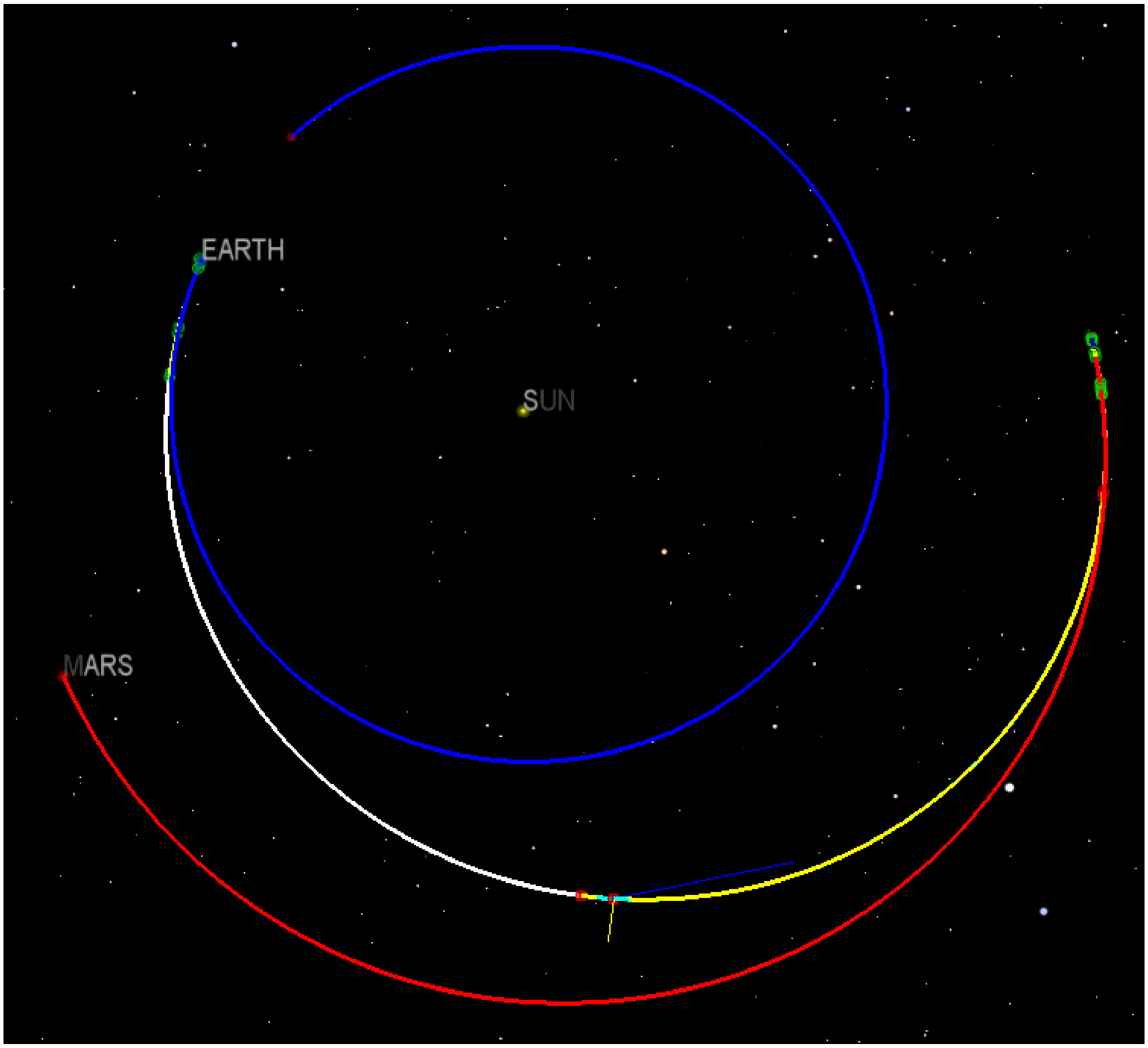


Figure 2: ESCAPADE Interplanetary Cruise, Sun-centered Ecliptic J2000 frame.

Figure 3 illustrates the *Blue*-Earth-*Gold* angle over time during the interplanetary cruise to show when the DSN can use MSPA to communicate with both spacecraft in the same aperture. The threshold within which MSPA closes the link budget is higher earlier in the transfer and smaller later in the transfer, but the 0.08 deg is a good first estimate for when MSPA may be achieved. One can see that the interplanetary cruise achieves MSPA shortly after three months into the cruise and retains it until MOI. Once at Mars the angular separation of the spacecraft shrinks and MSPA is available.

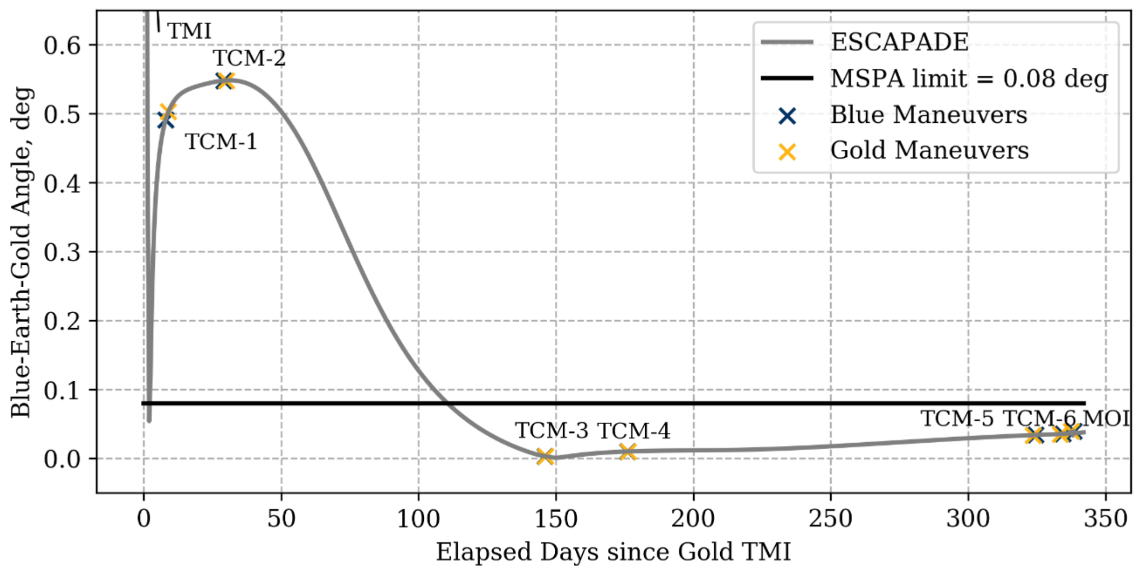


Figure 3: The angle between each ESCAPADE spacecraft and the Earth, to evaluate the timeline when MSPA is available with the DSN.

3. Trajectory Correction Maneuvers

Six TCMs are scheduled for each spacecraft during the cruise. TCM-1 is conducted nine days after the corresponding TMI; it will target the same TMI targets and therefore remove most of the TMI maneuver execution error. TCM-2 will be conducted approximately 3 weeks later, but such that both TCM-2B and TCM-2G are conducted two hours apart. This is desirable for the mission operators so that they may support both maneuvers in the same shift. In the same way, TCMs 3 and 4 are performed two hours apart. TCM-2 is performed if necessary to achieve MSPA early in the cruise. TCM-3 is the only large deterministic maneuver in the cruise; its purpose is to bring the two spacecraft together in an MSPA perspective until MOI. TCM-3 nominally transfers both spacecraft 96% of the way to the MOI targets; it holds back those final 4% in order to efficiently accommodate maneuver execution errors and to avoid intersecting the delivery covariance with Mars' impact disk. TCM-4 completes the shift to the MOI targets and cleans up the delivery dispersions from TCM-3. TCMs 5 and 6 are stochastic maneuvers that are used to refine the trajectory and target the MOI corridor.

Table 2: ESCAPADE TCM Strategy

	Mars B-Plane Target	Burn Epoch	Delta-V, m/s
TCM-1	TMI	TMI + 9 days	~20
TCM-2	TMI	TMI + 30 days	~1
TCM-3	96% of MOI	Blue: 25-Feb-2025 ET Gold: 25-Feb-2025 ET	16.60 9.31
TCM-4	MOI	TCM-3 + 30 days	2.71 2.14
TCM-5	MOI	MOI – 14 days	~1
TCM-6	MOI	MOI – 4 days	~0.1

4. Arrival at Mars

Figure 4 illustrates the B-Plane targets for each TMI and each TCM, relative to Mars' Sphere of Influence (SOI) and impact disk. The initial TMI targets are well outside the Mars SOI due to the geometry needed to achieve MSPA with respect to ground stations on Earth. TCM-3 targets 96% of the burn needed for the desired MOI B-Plane parameters and TCM-4 aims precisely at the desired MOI B-Plane targets. TCMs 5 and 6 are available for any final cleanup maneuvers needed before MOI. The *Gold* spacecraft arrives at Mars first, with an anticipated first close approach and MOI maneuver on 1-Sep-2025. Next, the *Blue* spacecraft makes its first close approach and MOI maneuver on 3-Sep-2025.

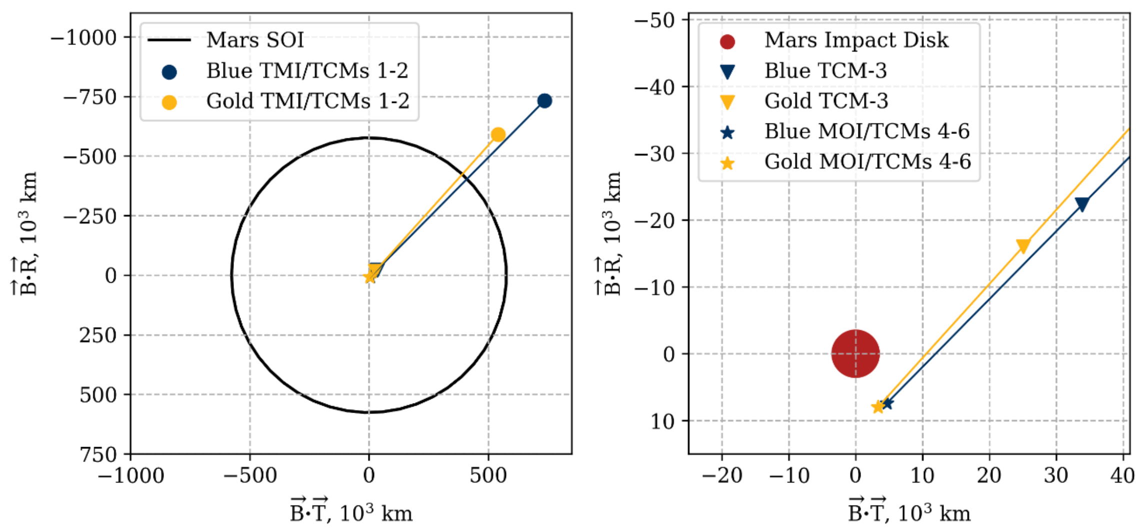


Figure 4: ESCAPADE *Blue* and *Gold* B-Plane targets for TMI and TCMs, relative to the IAU Mars Pole coordinate frame.

Mars Orbit Insertion

The Mars Orbit Insertion (MOI) Phase begins approximately one month before arrival at Mars. The two spacecraft enter a moratorium such that all attention is focused on executing the MOI safely. The *Gold* spacecraft arrives at Mars 48 hours before the *Blue* spacecraft and each target an MOI Corridor that is centered about a nominal aimpoint 450 km above the surface. A thrust arc centered around this passage is used to capture into an elliptical orbit, aiming for a period of ~87 hours, with variation due to maneuver execution. This insertion orbit is much smaller than it was in previous versions of ESCAPADE's design, given that the maneuver is now conducted with a chemical propulsion system. The maneuver is modeled and executed as an inertially pointed burn. The capture orbit is designed to accommodate all maneuver execution errors and also retain a large apoapse radius. The large apoapse radius permits early instrument check-out as the instruments pass into the pristine solar wind each apoapse and the Mars magnetosphere each periapse. The MOI Phase is complete when the spacecraft are in stable, safe orbits about Mars.

Table 3. ESCAPADE Mars Orbit Insertion Burns and Capture Orbits (IAU Mars Pole Frame)

Parameter	Blue	Gold
Burn Start Epoch, ET	02-SEP-2025 11:55:16.7789	01-SEP-2025 11:55:16.0945
Duration (s)	282.75	283.76
Longitude, α (deg)	-0.69	5.21
Latitude, β (deg)	-76.66	-75.79
Period (hours)	86.62	86.69
Radius of Periapse (km)	3845.5	3847.1
Radius of Apoapse (km)	90,653.6	90,702.9
Eccentricity	0.919	0.919
Inclination (deg)	63.60	63.85
Longitude of Node (deg)	75.12	75.06
Argument of Periapse (deg)	319.28	318.81

ORBIT REDUCTION PHASE

Once in orbit about Mars, the ESCAPADE spacecraft execute several maneuvers to reduce their orbits and establish safe and stable orbits.

Following the completion of the orbit insertion maneuvers, the spacecraft coast in orbit around Mars for two weeks. Each spacecraft then performs an apoapse reduction maneuver (ARM) at the following periapse, coast for two additional weeks, then perform a periapse reduction maneuver (PRM) at apoapse.

Each ESCAPADE spacecraft has its own associated targets for ARM and PRM. As with the orbits targeted during the orbit insertion phase, these targets are in preparation for downstream operations. Table 4 provides the targets for each maneuver on each spacecraft, as well as the reference burns used to achieve these targets. The ARMs target an orbital period while the PRMs target a periapse altitude, assuming the radius of Mars is 3396.19 km at all points. For each of these maneuvers, the burn is performed in an inertially fixed direction.

Table 4. ESCAPADE PRM & ARM Targets with Reference Thrust Arcs

Burn	Burn Start (Ephemeris Time)	Burn Duration (s)	Delta-V (m/s)	Target (Period, Periapse Alt)
ARM-B	18-SEP-2025 07:59:46.8078 ET	18.19	50.926	50 hours
ARM-G	19-SEP-2025 07:13:21.4533 ET	24.92	70.039	40 hours
PRM-B	02-OCT-2025 00:06:48.4297 ET	3.31	9.372	165 km
PRM-G	02-OCT-2025 16:20:07.6382 ET	3.71	10.604	155 km

This sequence's design is motivated by three influencing factors. First, the orbits must not intersect so that the spacecraft have no chance of collision. This is achieved by ensuring that *Gold*'s orbit is fully encapsulated by *Blue*'s orbit, in periapse and apoapse, sufficient to support expected maneuver execution errors. Second, the orbits must be safe in the presence of gravitational perturbations; the orbits shown here do experience gravitational perturbations such that the periapses rise over time during the quiescent coasting period. This achieves safety in a successful manner. Third, the orbits pass through the lower ionosphere and extend into the pristine solar wind during this coast period. This is important to test out and calibrate the instruments and to collect early scientific observations from this orbit.

TRANSITION TO SCIENCE FORMATION PHASE

Following the end of the solar conjunction, the spacecraft enter the Transition to Science Formation (TSF) phase. The TSF phase involves lowering the apoapse and periapse (which will have risen during the solar conjunction due to perturbations) to the level of the science orbit (nominally 8,400 km and 160 km of altitude, respectively), inserting the spacecraft into matching orbital planes and targeting a desirable leader-follow profile. Following the completion of the TSF phase, the orbital period of the spacecraft must be nearly identical to maintain a near-constant following duration. The spacecraft must also have very similar periapsis altitudes (within 10 km) so that they are sampling similar spaces above Mars, which also necessitates that they have very similar eccentricities. The orbital planes must be identical to within 1 degree following the completion of the TSF phase. Finally, it is desirable for the spacecraft to be approximately 30 minutes apart in their leader-follower arrangement initially, with *Blue* as the lead. The TSF phase is composed of either 8 or 9 burns, with each being dependent upon the results of prior burns as the spacecraft work towards both the target orbit and the leader-follower arrangement.

TSF-G1, TSF-B1 and TSF-B2

The first maneuver of the TSF phase is performed by the spacecraft with the larger longitude of node, including an offset for the *Gold* spacecraft; the reasoning for this offset is given below. For the nominal case, and thus the case discussed herein, it is therefore determined that the first *Gold* TSF burn (TSF-G1) come before the first *Blue* TSF burn (TSF-B1).

TSF-G1 is performed near the first periapse following the completion of the coasting period which covers the solar conjunction. This burn reduces the apoapse by 75% of the difference between the apoapse altitude before the burn and the nominal science apoapse altitude. Only 75% of the difference is targeted to avoid reducing past the science apoapse while accounting for maneuver execution error. Following the burn, the remaining change necessary to reach the target will be determined and covered by a later burn. The burn is also set to reduce the difference in argument of periapse (AoP) between the spacecraft by 80% and to bring the inclination of the orbit 80% closer to a target value between 65 and 75 degrees. These changes are only made fractionally to prevent over-correction and to provide opportunities to continue modifying the parameters in later maneuvers, thus being more efficient with fuel overall especially in the presence of maneuver execution errors.

Following the lowering of the *Gold* apoapse altitude, a negative rate of change is introduced to the longitude of node due to spherical harmonic perturbations. It is for this reason that *Blue* occupied the lower altitude of apoapse prior to the start of the TSF phase, and that the order of burns in this segment of the phase is determined in the manner described above. TSF-B1, which aims to lower the apoapse altitude by 96% of the difference to the target, introduces a negative rate of change to the longitude of node with greater magnitude than that introduced to the *Gold* orbit by TSF-G1, as the resulting apoapse altitude is lower. It is therefore necessary that the *Gold* longitude of node be lower than the corresponding value for *Blue* by some margin when TSF-B1 is performed, so that each spacecraft will soon have the same longitude of node value; this matching time will be the execution time of a later maneuver within this phase.

TSF-B1 also aims to reduce the difference in AoP between the spacecraft by 60%, and to move the *Blue* orbital plane 70% towards the target inclination.

The second burn in the TSF phase performed by the *Blue* spacecraft, TSF-B2, is performed at the first apoapse passage at least 8 days following TSF-B1 and aims to lower the Blue spacecraft periapse to the target altitude. It also continues to adjust the orbital plane, aiming to reduce the difference in AoP between the spacecraft by 20% and to move the *Blue* inclination 94% towards the target inclination.

Lead Time Targeting

The remaining burns work to target the desired leader-follower arrangement while inserting the spacecraft into the desired orbit. The first burn in this section, TSF-G2, is designed to match the rate of change of the longitude of node between the two spacecraft when the longitude of node values are within 0.37 degrees. This is accomplished by lowering the *Gold* apoapse altitude so the semi-major axes (the factor which determines the rate of change imparted upon the longitude of node by spherical harmonic perturbations) of the two spacecraft are the same. It must be assumed that TSF-B2 accomplished the periapse reduction perfectly, as it is likely to be necessary to perform TSF-G2 too soon after to retrieve data on the performance of that burn.

TSF-G2 is performed when the Blue lead time is between 130 and 270 minutes, and continues adjusting the AoP and inclination, targeting a 50% reduction in AoP difference and 30% towards the target inclination. Further changes in the semi-major axis of each spacecraft following the completion of this burn will be small enough that the rate of change of the longitude of node will not change significantly.

TSF-B3 and TSF-G3 continue to lower the apoapse altitudes of the spacecraft; these maneuvers do not account for lead times. TSF-B3 is performed at the first *Blue* periapse to occur at least 5 days after TSF-G2. It aims reduces the apoapse altitude 70% to the science target, reducing the difference in AoP between the spacecraft by 100% and bringing the inclination 100% to the target. Following TSF-B3, the lead time will rise slowly as the *Blue* orbit is slightly smaller. TSF-G3 is performed at the first *Gold* periapse at least 1 full day after TSF-B3 and reduces apoapse altitude approximately to the science target. It also seeks to completely eliminate any remaining difference between the spacecraft AoP and to bring *Gold* to the target inclination.

Following the completion of TSF-G3, *Blue* has a periapse altitude approximately at the science target while *Gold* has an apoapse altitude approximately at the science target. The *Gold* periapse altitude and *Blue* apoapse altitude are both very close to the respective science targets. There should be a small positive rate of change in the lead time.

TSF-G4 is performed at the first apoapse at least 5 days after TSF-G3 with the lead time no more than 400 minutes. This maneuver drops the *Gold* periapse altitude to the science target (and cleans up any errors remaining in AoP and inclination).

Following TSF-G4, the lead time rate of change should be negative (as the *Gold* satellite has a smaller semi-major axis) with a large enough magnitude to meet the requirements for TSF-B4 described below within a couple of weeks, before the epoch intended for the start of the science phase. However, some simulations with error introduced to burn performance have produced results in which this magnitude is small, meaning it would take a long time to meet these requirements. In these cases, it would be necessary to insert a burn between TSF-G4 and TSF-B4, which would bring the maneuver count to 9 for that scenario. This additional maneuver uses the nitrogen gas RCS system and works to increase *Blue*'s orbit to increase the rate of change of the lead time.

Changes in *Blue* lead time are dictated by the orbital periods of the spacecraft. Following TSF-G4, both spacecraft should have periapse altitude at the science target, the *Blue* apoapse altitude should be higher than the science target, and the *Gold* apoapse altitude should be at the science target. *Blue* should therefore have the larger semi-major axis and larger period, causing the lead time to shrink. In cases where the lead time does not shrink or shrinks at a very slow pace, it must be the case that, due to maneuver errors, one of the three apsis altitudes which should be at the science target has missed its mark, or the *Blue* apoapse altitude reached the science target earlier than intended. This error causes the spacecraft to have similar periods, and the lead time remains relatively constant.

An extra burn inserted to correct this issue before TSF-B4 to ensure the spacecraft reach the science orbit prior to the intended start of the science phase can therefore be on either satellite, depending upon which of the above-described errors is causing the issue. If one of the *Gold* apses has an altitude significantly above the science target, a small burn could be performed to correct that issue. If the *Blue* periapse altitude is significantly below the science target, a correction burn could be performed to correct that issue. Finally, if all three of those apsis altitudes are within some tolerance of the science target, a burn could be performed to raise the *Blue* apoapse altitude by some amount, increasing the *Blue* period and causing the lead time to shrink. After collecting information on the results of TSF-G4, if the lead time is not decreasing at a rapid enough rate, the performance of one of these correction burns should clean things up so that TSF-B4 can be performed before the science phase is slated to start.

TSF-B4 is performed at the first *Blue* periapse following TSF-G4 (or TSF-G5) at which the lead time is between 24 and 40 minutes. This maneuver lowers the *Blue* apoapse to the science target (and completes cleanup of AoP differences and inclination targeting). Following the completion of this final maneuver, both spacecraft should have the same orbit shape and plane. Being in the same orbit, the spacecraft should have the same orbital period and the lead time should be constant. Time profiles of the orbital shape and plane specifications for each spacecraft and the lead time during a nominal run through the TSF phase are shown in Figures 5 – 7.

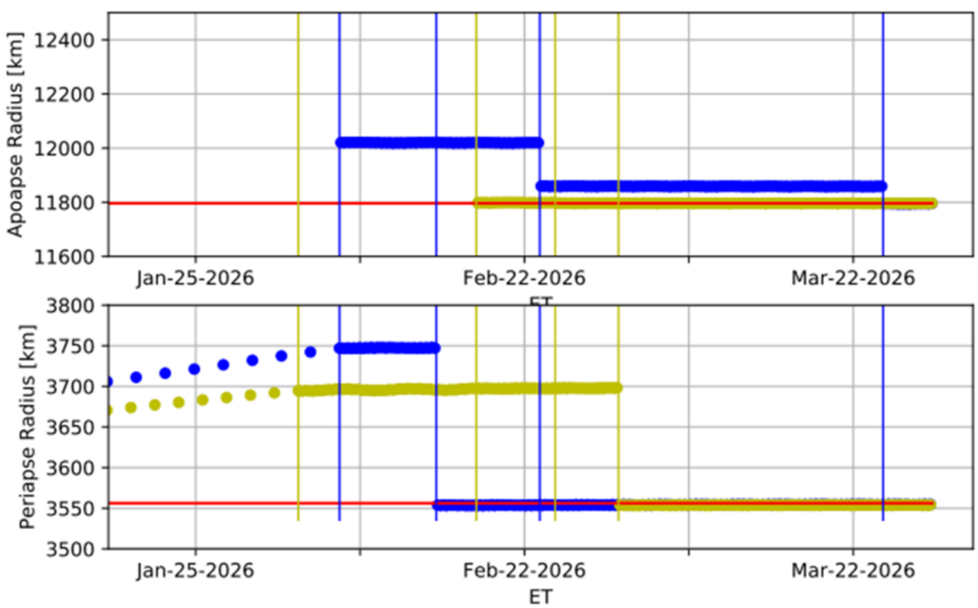


Figure 5. The TSF Phase's nominal timeline for periapse and apoapse radii. The red lines are the science orbit targets; blue and gold correspond with the appropriate spacecraft.

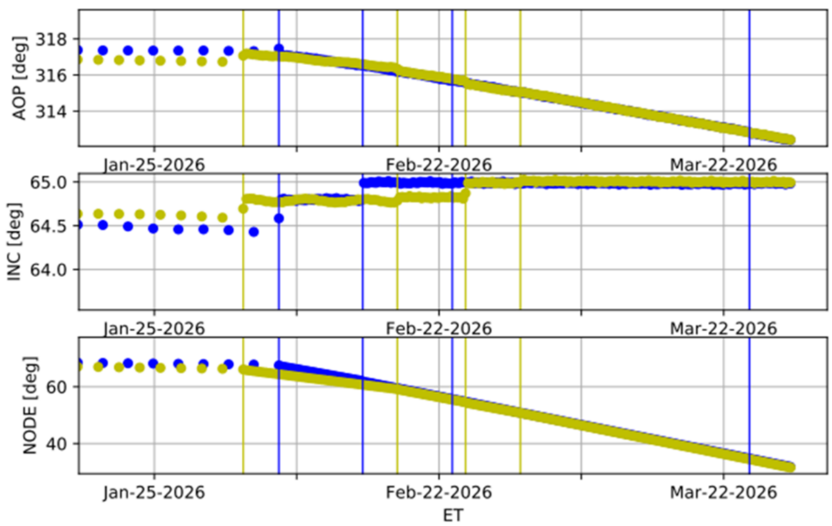


Figure 6. The TSF Phase's nominal time profile for the argument of periapse, inclination, and longitude of node, all in the IAU Mars Pole coordinate frame, achieving the same orbital geometry at the start of science.

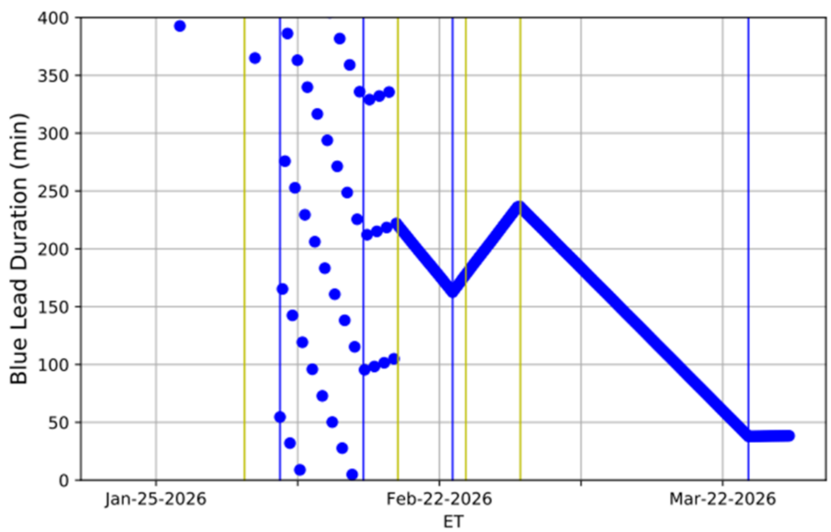


Figure 7. The TSF Phase's nominal timeline for the duration that *Blue* leads *Gold* in orbit about Mars.

PRIMARY SCIENCE PHASE

Once the two spacecraft are in their leader-follow arrangement then Science Campaign A may begin. This continues for six months, followed by a transition to Campaign B, and five months for Campaign B. The nominal campaign orbits are illustrated in Figure 8 and lead duration profile in Figure 9.

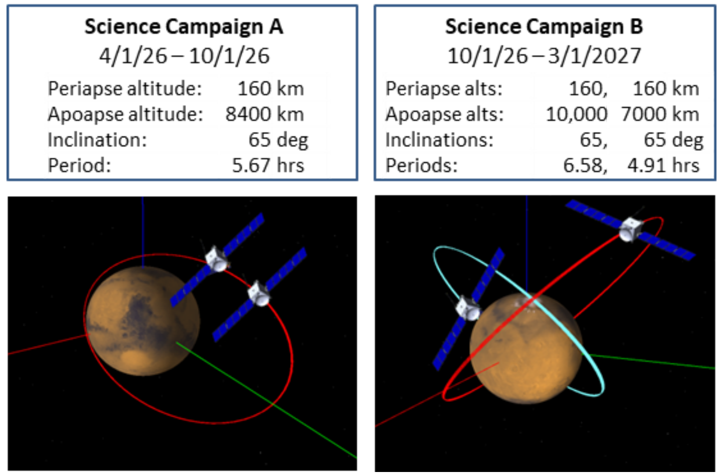
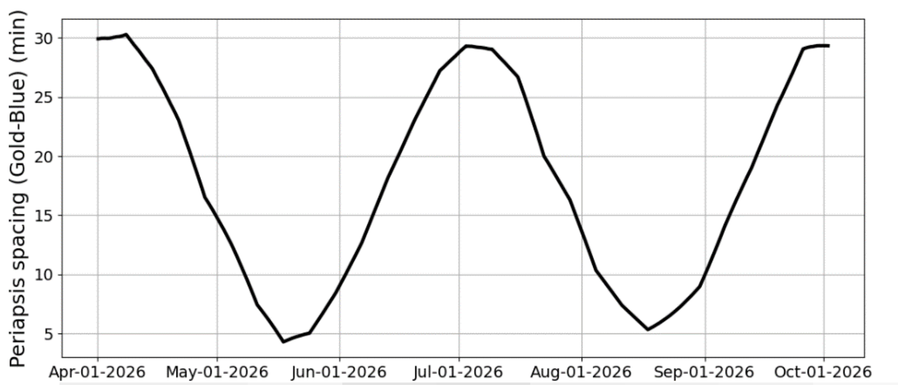


Figure 8. The nominal science orbits for Campaigns A and B



Campaign A

The two spacecraft will be in approximately the same orbit during Campaign A, with *Blue* leading *Gold* by an amount of time that varies between 4 and 30 minutes. The spacecraft alternate performing weekly stationkeeping maneuvers using the nitrogen propulsion system to control the target periapse density and formation spacing. The spacecraft with the most nitrogen performs the formation spacing portion of the stationkeeping in order to keep nitrogen balanced. ESCAPADE's science corridor maintains that the periapse dip into the atmosphere where the peak density is at least 0.07 kg/km^3 as predicted by MarsGRAM 2010. The density observed may be higher or lower than that, but the corridor is defined by the density model. Each weekly stationkeeping maneuver adjusts the mean period of one spacecraft to achieve the target spacing by the next stationkeeping maneuver and the periapse radius to maintain the science density corridor. Campaign A continues for six months in the reference mission.

Transition to Campaign B

The transition from Campaign A to Campaign B involves one spacecraft raising its apoapse and the other spacecraft lowering its apoapse. Both spacecraft execute a maneuver at periapse in the velocity or anti-velocity direction to raise or lower their apoapsis with *Gold*'s transition occurring two days after *Blue*'s. From this point forward, the spacecraft are managed independently.

Campaign B

Mars' J_2 effect will influence the two spacecraft orbits differently, once they have different semi-major axes and eccentricities. Thus, the relative node of the two orbits will grow, as will the relative location of their periapses. As they drift apart, they will be able to sample spatially different regions of the Mars state space simultaneously. Their periapse altitudes will continue to be maintained via bi-weekly stationkeeping maneuvers to achieve the desired density corridor. They will continue to sample ionosphere states, but the relative local solar time of those samples will vary. Campaign B lasts for five months nominally.

Figure 10 illustrates the Primary Science Phase including both Campaign A and B.

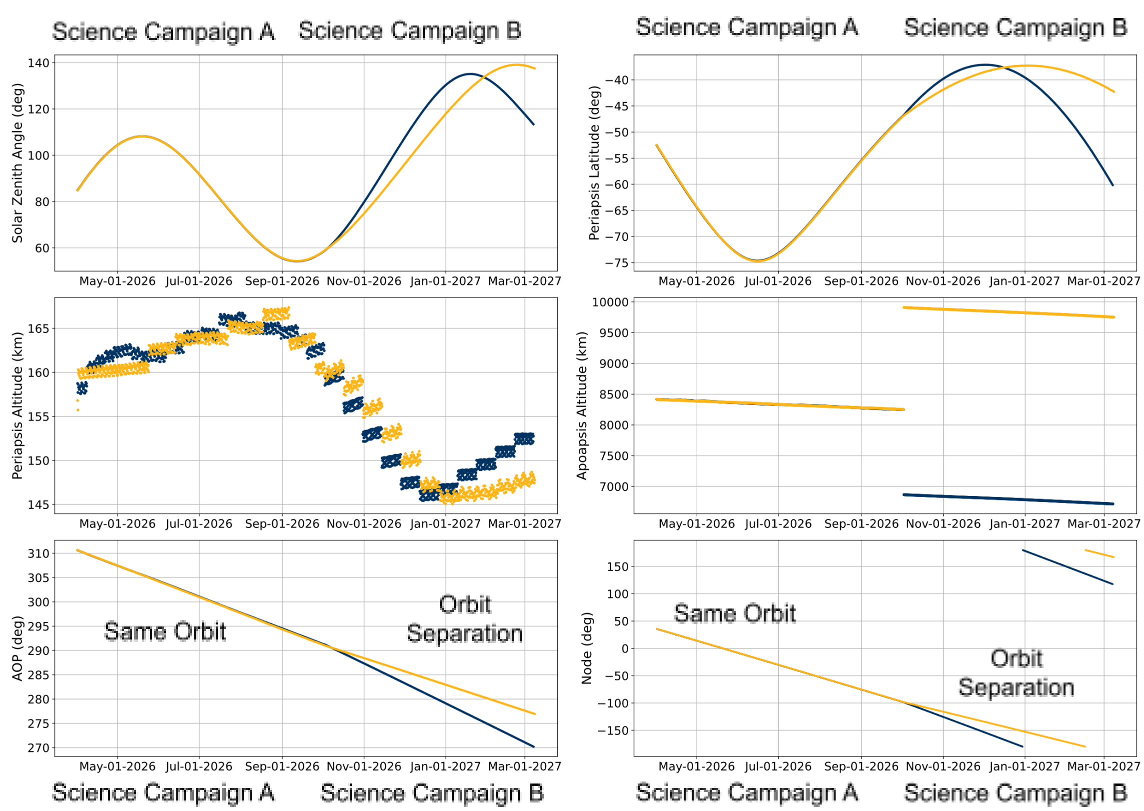


Figure 10. ESCAPADE's orbit profile for the primary science mission.

Decommissioning

At the end of the mission both spacecraft will be decommissioned according to NASA policy. This involves communicating their final states to the NASA planetary protection office as well as the Mars community. Their orbits will naturally degrade over time and will eventually enter the Martian atmosphere. The ESCAPADE planetary protection plan does not require prevention of this; rather, it involves maintaining a sufficiently low number of spores and ensuring that the probability of any of them surviving the Mars atmospheric entry, break-up, burn-up, impact, and subsequent life on the surface of Mars is sufficiently low.

Maneuver Summary and DV Budget

The details of the DV budget require far too much description to fit within the scope of this paper, yet a summary description is provided here. The main engine is qualified for 18 restarts; 17 restarts are in the baseline and one is unallocated.

The baseline launch involves seven maneuvers for each spacecraft. The Earth Burn Number 1 (EBN-1) is performed by the launch vehicle upper stage, placing the spacecraft in a 1.6-day orbit or higher. The remainder of the burns include:

- EBN-2 (Earth Burn Number 2): raises the apogee, targeting an orbital period near 6 days.
- EBN-3 (Earth Burn Number 3): raises the apogee, targeting a large orbit of 25 or more days.
- OCM-1 (Orbit Correction Maneuver 1): cleans up navigation errors after EBN-3.
- EBN-4 (Earth Burn Number 4): first of two opportunities to change the plane.
- EBN-5 (Earth Burn Number 5): second of two opportunities to change the plane.
- OCM-2 (Orbit Correction Maneuver 2): cleans up navigation errors and targets the TMI state.
- OCM-3 (Orbit Correction Maneuver 3): cleans up navigation errors and targets the TMI state.
- TMI (Trans-Mars Injection): targets the interplanetary cruise

The OCM-3 maneuver uses the RCS system; the others are main engine burns for a total of at most 7 main engine burns. If the launch is better suited then fewer maneuvers are required, down to even zero for aa direct-to-Mars rideshare.

The interplanetary cruise involves six TCMs per spacecraft. TCM-1 and TCM-3 are expected to be main engine burns; the others are RCS maneuvers. TCM-3 is the deterministic maneuver that is used to bring the two spacecraft into MSPA early in the cruise. It is small enough to permit RCS to clean up maneuver execution errors.

The Mars Orbit Insertion is the 10th allocated main engine maneuver.

The Orbit Reduction Phase uses two main engine burns for each spacecraft, ARM and PRM.

The Transition to Science Formation Phase involves four main engine burns on each spacecraft and a contingency RCS maneuver if necessary: TSF-1 through TSF-4.

The Science Phase involves one main engine burn to transition from Campaign A to Campaign B, as well as many RCS stationkeeping maneuvers.

The DV allocations for each phase are summarized in Table 5, including contingency allocations. The contingency allocations have been developed from a worst-case contingency in each phase. The worst-case contingency for the Launch and Orbit Raise Phase involves missing EBN-3 and executing it six days later. The worst-case contingency for the Interplanetary Cruise

Phase involves recovering from a 5-minute restart during one of the TMIs (not both). The worst-case contingency for the Orbit Reduction and Transition to Science Phase involves recovering from a 5-minute restart during one of the MOIs (not both). One can see that there is substantial propellant and N_2 margin aboard the spacecraft, even with a worst-case launch scenario, in the presence of all contingencies.

Table 5. ESCAPADE DV Budget

Phase	DV (m/s)	Initial Mass (kg)	Prop Mass (kg)	N_2 Mass (kg)
Orbit Raise	392	396.07	51.458	0.292
Obit Raise Contingency	42.1	344.52	4.977	0.000
TMI	600	339.34	63.821	0.010
TCMs	37.8	275.51	4.298	0.667
TCM Contingency	2.2	270.79	0.206	0.000
MOI	685.61	270.34	57.303	0.010
Orbit Reduction	593.48	213.03	40.955	0.328
Reduction Contingency	12.5	171.92	0.741	0.000
Science A	7.48	171.00	0	2.452
A-->B	65	168.55	4.005	0.010
Margin			9.09	5.58
Total	2442.31		244.000	12.070

Summary

The ESCAPADE mission design described here demonstrates the sequence of design phases that are needed to accept two independent spacecraft from a rideshare launch that could be as inconvenient as a Sun Synchronous orbit and yet transfer both spacecraft to two different science campaigns at Mars. The design presented here minimizes operational complexity where possible given the needs of the mission. The choreographed sequence of maneuvers needed to safely and robustly place the two vehicles into the same science orbit without risk of collision is designed to be supported by one navigation team with efficient timetables between each navigation design. ESCAPADE's science will be the first dedicated multi-point scientific investigation conducted about another planet.