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MISSION DESIGN FOR THE EMIRATES MARS MISSION

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The United Arab Emirates is launching the Emirates Mars Mission (EMM) to Mars in 2020 to explore the atmospheric dynamics of Mars on a global, diurnal, sub-seasonal scale. The mission design involves a Type I transfer to Mars, coordinated with many other simultaneous Mars missions, most of whom share the same network of ground tracking stations. The Mars Orbit Insertion places the EMM Observatory, *Amal*, into a very large, elliptical capture orbit. Three Transition to Science Maneuvers are optimized under uncertainty to transfer the spacecraft into a unique 20,000 km x 43,000 km, ideally shaped and oriented to achieve the EMM science objectives.

INTRODUCTION

The Emirates Mars Mission (EMM) is a strategic initiative established by the United Arab Emirates' President, His Highness Sheikh Khalifa Bin Zayed Al Nahyan and by the UAE's Vice President and Prime Minister, His Highness Sheikh Mohammed Bin Rashid Al Maktoum on 16 July 2014. Directed by Mohammed Bin Rashid Space Centre (MBRSC), EMM is a collaborative effort between MBRSC, the Emirates Institution for Advanced Science & Technology (EIAST), the University of Colorado Boulder's Laboratory for Atmospheric and Space Physics (LASP), Arizona State University's School of Earth and Space Exploration (SESE), and the University of California at Berkeley's Space Sciences Laboratory (SSL).

This paper describes the EMM mission design, including the launch strategy, the interplanetary cruise, the insertion into Mars orbit, the transition to EMM's science orbit, and the science orbit. Several key trade studies are summarized to illustrate how this design has been developed.

The EMM observatory, *Amal*, also known as the *Hope Probe*, will launch in the summer of 2020, arriving at Mars in early 2021. It will spend about 75 days commissioning in orbit about Mars before delving into a scientific investigation lasting an entire Martian year in its operational orbit about Mars. Its mission may be extended as long as the orbiter has resources to continue. When its mission and all extended missions are complete, it will be placed in a safe configuration and left in a safe, stable orbit about Mars.

EMM's unique orbit is illustrated in Figure 1, with other missions' science orbits for scale. This orbit provides a continuous view of Mars never before achieved, yielding access to global, diurnal mappings of the Martian atmosphere from the surface of Mars to its exosphere, within relatively short timescales.

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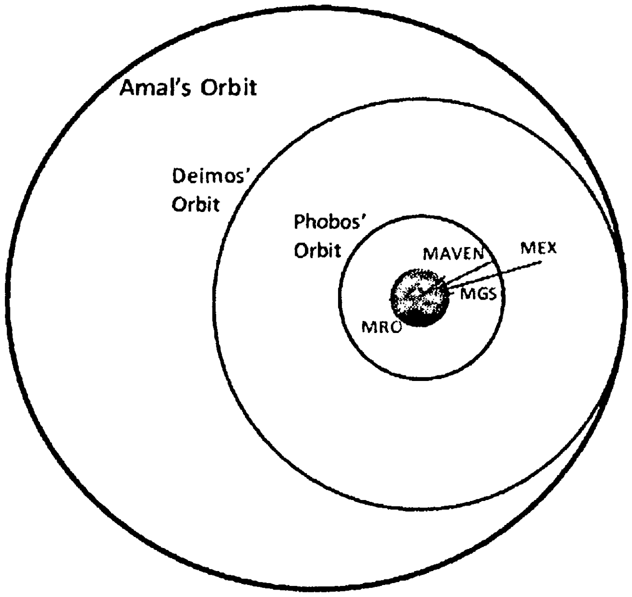


Key Features:

- Periapse altitude: 20,000 km
- Apoapse altitude: 43,000 km
- Orbital period: 55 hours
  3 orbits per week
  ~2.24 sols
- Inclination: 25 deg
- Periapse placed near equator
- Primary science collection starts ~April 2021

Figure 1. The EMM Science Orbit, with other orbits shown for scale. The orientations of the orbits are representative only.

EMM will collect observations about the Mars system using three remote sensing instruments, sensitive to visible, infrared, and ultraviolet wavelengths. EMM will provide the measurements necessary to better understand atmospheric circulation and weather in the Martian lower atmosphere. By also measuring the upper layers of the atmosphere, EMM measurements will help to determine how energy and particles are transported upward, leading to escape of atmospheric particles from the gravity of Mars. While some individual aspects of the measurements have been made previously at Mars, the unique combination of instruments and orbital coverage will enable an exciting and completely new understanding of how the Martian atmosphere works.

SCIENCE OBJECTIVES

EMM explores the atmospheric dynamics of Mars on a global, sub-seasonal scale, providing the measurements necessary to understand atmospheric properties aligned with the following science objectives:

1. Characterize the state of Mars' lower and middle atmosphere (<60 km) on global scales and its geographic, diurnal, and seasonal variability.
2. Correlate rates of thermal photochemical atmospheric escape with conditions in the collisional atmosphere (<200 km).
3. Characterize the spatial structure and variability of Mars exosphere.

To date, measurements of the Martian atmosphere have been made at very limited timeframes, leaving more than 80% of Mars' diurnal cycle unexplored. EMM investigates Mars' geographic regions at all times of day, facilitating understanding of both global circulation and energy transport. Data returned from EMM will reveal the connection between these conditions in the lower atmosphere and the escape of hydrogen and oxygen from the upper atmosphere, a process that may have been responsible for Mars' transition from a thick, wet atmosphere billions of years ago to the cold, thin, arid atmosphere observed today.

EMM's scientific objectives have been mapped into four investigations.

- **Investigation 1.** Determine the three-dimensional thermal state of the lower atmosphere and its diurnal variability on sub-seasonal timescales.
- **Investigation 2.** Determine the geographic and diurnal distribution of key constituents in the lower atmosphere on sub-seasonal timescales.
- **Investigation 3.** Determine the abundance and spatial variability of key neutral species in the thermosphere on sub-seasonal timescales.
- **Investigation 4.** Determine the three-dimensional structure and variability of key species in the exosphere and their variability on sub-seasonal timescales.

These four investigations are satisfied by coordinating observations taken from three instruments: the Emirates eXploration Imager (EXI), the Emirates Mars InfraRed Spectrometer (EMIRS), and the EMM Mars Ultraviolet Spectrometer (EMUS). Amal's three instruments, placed in context of the Observatory as a whole, are illustrated in Figures 2 and 3. All three EMM instruments are co-aligned and co-located on a panel on the spacecraft +Y axis.

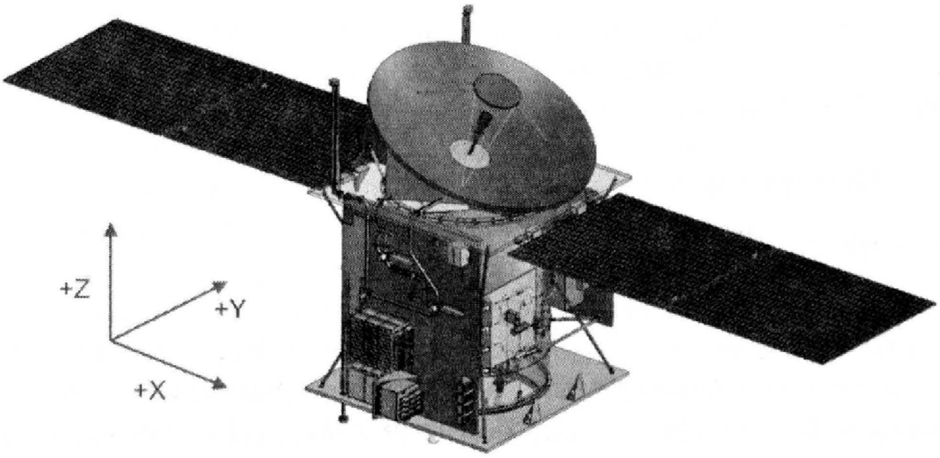


Figure 2. The high-level view of the Observatory.

EXI is a six-band visible imager (205nm-680nm) designed to provide high resolution (less than 10km) mapping of ozone abundance as well as cloud and dust optical depth.

EMIRS is a thermal infrared emission spectrometer (6-40+um) designed to provide high fidelity mapping of vertical temperature profiles as well as column abundance of dust, water vapor, and ice. It is an interferometric thermal infrared spectrometer operating with 5 & 2.5 cm^{-1} spectral sampling, enabled by a CVD diamond beamsplitter and state of the art electronics. This instrument utilizes a 3×3 square array detector to quickly (2-4 seconds per set of 9 spectra) make high-precision atmospheric measurements over the entire visible Martian disk. Each detector has a beamwidth of approximately 6 milliradians. The EMIRS instrument captures the integrated, lower-middle atmosphere dynamics, using a scan-mirror to make global images per day at $\sim$100-250 km/pixel near apoapsis. The EMIRS scan-mirror capability also enables a full-aperture calibration, allowing for highly accurate radiometric calibration ($<1\%$ projected performance) to robustly measure atmospheric and surface properties.

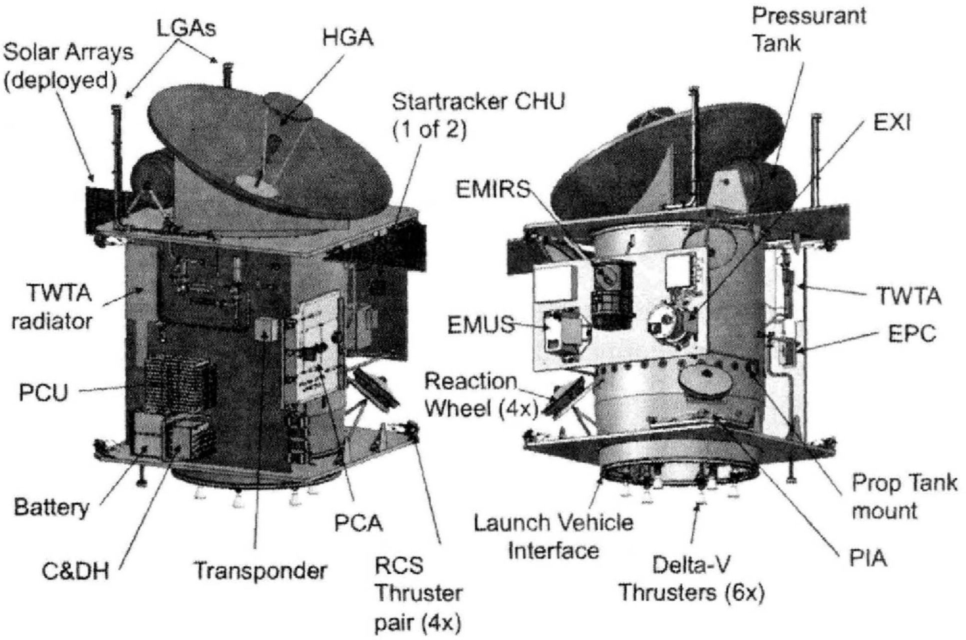


Figure 3. The Observatory's main components, including the three EMM instruments.

EMUS is a wide-angle far-ultraviolet (100nm-170nm) spatial and spectral mapper designed to measure oxygen, carbon, and carbon monoxide brightness in the thermosphere. EMUS will observe the thermosphere of the Martian atmosphere.

IMPLEMENTATION TRADES

Science Orbit Selection

The EMM Science Orbit is the product of a rigorous trade study that has investigated a wide range of possible orbits and mission designs, settling on one that fits the specific needs of the EMM program. The EMM Science Orbit is unique in the history of Mars exploration: no previous Mars mission has aimed for such an orbit. The orbit provides a vantage point from which the Observatory is able to collect global, diurnal, temporal observations from Mars' surface out to the exosphere. It is operationally low-risk, requiring no station keeping or aerobraking maneuvers. It offers opportunistic science in addition to the mission's primary scientific objectives.

The science orbit trade study has considered a wide variety of possible orbits, including:

- Circular vs. elliptical orbits;
- Low-altitude vs. medium-altitude vs. high-altitude;
- Synchronous vs. asynchronous orbits;
- Equatorial vs. low-inclined vs. high-inclined vs. polar orbits;
- Prograde vs. retrograde orbits;
- Conventional orbits vs. halo orbits about L_1 or L_2 vs. other Sun-Mars three-body orbits.

The trade study has first examined which orbits provide a platform to collect EMM's global, diurnal, temporal scientific observations. Most orbit types are eliminated with careful consideration of each component of the science investigation.

Global Observations. EMM's first and second objectives require the observatory to observe the majority of Mars' surface and lower atmosphere every 10 days. Global observations may be made from most orbit types. The orbit types that do not provide sufficient global coverage include equatorial orbits since they do not provide observations of the polar regions of Mars and areosynchronous orbits since their groundtracks are anchored to the surface of Mars as Mars rotates. The 1:1 resonant areosynchronous orbit is particularly bad, since it only presents one face of Mars to the spacecraft, but other resonances are poor too if the resonant cycle is under 10 days.

Diurnal Observations. EMM's first and second objectives also require that the global observations be made from many lighting conditions every 10 days. Some orbit types provide better opportunities to view Mars' surface and atmosphere at all lighting conditions than others. First, high-altitude orbits provide more opportunities to view any given location at different lighting conditions. From a high vantage point, Amal can observe regions of Mars at several different lighting conditions simultaneously. Highly inclined and polar orbits are not good options for diurnal observations since they are more tied to a particular region of lighting conditions. The extreme case is that of a sun-synchronous orbit: these orbits only view their ground track at the same lighting conditions every orbit. Finally, halo orbits and other similar three-body orbits about L_1 and L_2 are not good candidates because they only see a narrow range of lighting conditions.

Temporal Sub-Seasonal Scales. The objective of the mission is to obtain global, diurnal observations over a reasonably short time scale. Low-altitude orbits may achieve global, diurnal observations of the surface and lower atmosphere, but not over a short duration of time. Short-cycle resonant orbits do not achieve the global, diurnal observations, but have short time scales; long-cycle resonant orbits do achieve the observations, but are slow to repeat. A resonant orbit with a repeat cycle corresponding to the timescale of interest satisfies the sub-seasonal requirement, provided the timescale is sufficient to achieve global, diurnal observations of the targets of interest.

Observing Strategy. The EMIRS observations benefit by having lower altitudes while the EMUS observations benefit by having higher altitudes for exospheric observations. An elliptical orbit provides a good balance of both needs, while also providing some differing vantage points throughout each Martian year. The EMM instruments and observatory prefer prograde orbits over retrograde orbits because smearing is minimized with nadir-pointing observations.

The Narrowed Trade Space. The orbital trade space that survives each of the filters described here is quite limited: it includes prograde, elliptical orbits with relatively high periapse and apoapse altitudes. The orbital period should be asynchronous over timescales of a week or less. Further investigation within these constraints has revealed that an inclination of 25 degrees is optimal: it provides a minimally acceptable amount of polar observations to satisfy the science product development and otherwise maximizes the diurnal surface area covered by the mission.

Detailed trade studies have continued to refine the trade space. It is desirable to have an orbital period far from 24.6 hours – far from the aerosynchronous orbit. Larger orbital periods work well and require significantly less orbit insertion fuel than low orbits. Strong, low-period resonances are an exception, since they do not provide global, diurnal maps before repeating – the 2:1 resonance is the notably poor resonance, occurring at an orbital period of approximately 49 hours. The studies begin converging at orbital periods near 56 hours, which is operationally convenient: the observatory would travel around Mars three times per week. Final refinements observed that an orbital period of

55 hours is very near optimal, having an orbital period of approximately 2.25 sols. This is achieved with a periapsis altitude of 20,000 km and an apoapsis altitude of 43,000 km. These values balance the needs of each instrument and also produce a ground track with a useful feature: near periapsis, the ground track of the spacecraft slows nearly to a stop as the spacecraft's motion matches the rotation rate of Mars. This provides a good opportunity to study one face of Mars with minimal smear as it travels through a range of local solar times. This opportunity repeats with a different face of Mars every 2.25 sols.

The EMM Science Orbit. The EMM Science Orbit is approximately a 4:9 resonant orbit: Amal traverses 4 orbits about Mars in 9 sols. The motion of Amal near its periapsis passage is nearly locked to the surface of Mars, such that it can study one face of Mars carefully as that face travels through different lighting conditions. Then, as Amal travels out to apoapsis and traverses its apoapsis, Mars rotates faster than Amal orbits. This permits Amal to study many regions of Mars at similar lighting conditions over a short time. The next periapse passage occurs approximately 2.25 sols after the previous passage, meaning that Mars' surface is 90 degrees rotated from the previous periapsis passage. Hence, each of four consecutive periapsis passages permits Amal to study a different cardinal face of Mars before repeating the cycle. Investigations 1 and 2 have a timescale of 10 days: this orbit provides some overlap and redundancy and achieves this cadence.

Figure 1, above, illustrates the EMM Science Orbit relative to other orbits about Mars. The other Martian orbiters are in inclined orbits, though not precisely polar as indicated in the graphic. Figure 4 illustrates the groundtrack of Amal's Science Orbit. One can see that each orbit traverses the planet several times, coming to relative rest near periapse. Each orbit also reaches latitudes as high as 25 deg away from the equator in both directions. The longitude of periapse moves approximately 90 deg every orbit; it is not required to move precisely 90 deg, so it will likely drift throughout the mission.

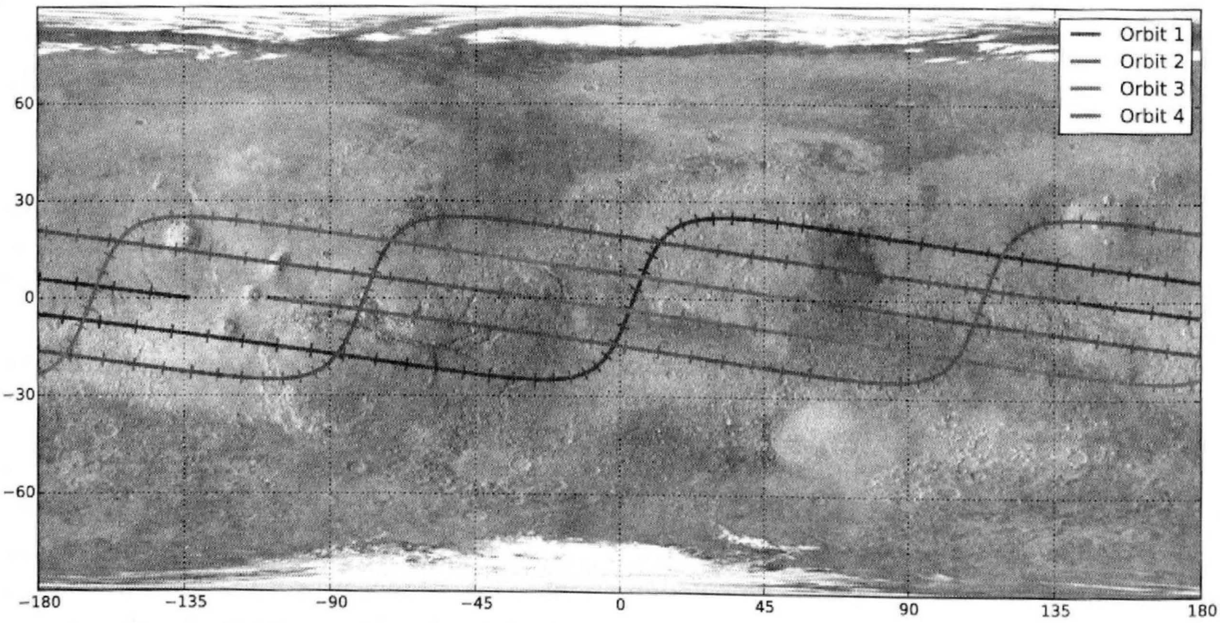


Figure 4. The EMM Science Orbit groundtrack for four orbits, with 1-hour tickmarks.

Interplanetary Cruise Trajectory Options

The early EMM mission design considered many interplanetary cruise options. Each option traded the following parameters, attempting to find an optimal combination of each:

- **Launch Date**: The project prefers to launch as late as possible, provided that the mission arrives at Mars prior to December 2nd, 2021, the 50th anniversary of the UAE.
- **Δt, Transfer Duration**: There are some penalties to the mission if the transfer duration is very long, since the spacecraft and ground system would need to operate longer prior to the arrival at Mars.
- **Arrival Date**: The objective is to arrive at Mars prior to December 2nd, 2021.
- **C_3, Launch energy parameter**: equal to twice the specific energy of the spacecraft ($C_3 = 2\varepsilon$); also equal to the square of the hyperbolic excess velocity ($C_3 = V_\infty^2$). The objective is to minimize this parameter in order to launch on a smaller launch vehicle and/or have a wider launch period.
- **DLA**: Declination of the Launch Asymptote in a reference frame whose $x-y$ plane is aligned with Earth's equator. The declination is constrained by the launch site: a launch vehicle can target any declination less than or equal to its launch site's latitude without penalty; declinations further from zero require plane changes that penalize the launch vehicle's performance.
- **Gravity Assists** during the interplanetary cruise. It is possible to fly by Earth or Venus during the cruise to Mars. These involve additional operations costs and complexity, penalizing those interplanetary options.
- **V_∞ at Arrival**: The higher the spacecraft's arrival V_∞, the more fuel is required to get into orbit about Mars. Thus it is desirable to minimize the arrival V_∞.
- **Declination of V_∞ at Arrival**: The ideal declination of the arrival V_∞ vector, relative to Mars' equator, would be approximately ±25 degrees, permitting the spacecraft to enter a Capture Orbit that is coplanar and aligned with the target Science Orbit. Any deviation from that requires fuel to adjust.

Each of these transfer parameters was compared to identify the best transfer for EMM.

Interplanetary Transfer Options

The following transfer options exist for EMM:

- Type I. This type of transfer requires the least amount of time; the spacecraft travels less than 180° about the solar system before arriving at Mars.
- Type II. This transfer type involves orbital transfers that travel between 180° and 360° about the solar system. These typically extend the cruise a handful of months compared to a Type I transfer.
- Type III. This transfer type involves traversing between 360° and 540° about the solar system. This is useful when the planets do not line up until the spacecraft has flown one circuit about the Sun.

- Type IV. This transfer type involves traversing between 540° and 720° about the solar system, i.e., it is a complete circuit plus a Type II.

- Type V+. The trend of transfer types continues, but transfers that traverse two or more circuits about the Sun require far too much transfer duration to be considered.

- Earth Flyby options. One can take any transfer type listed above and launch 6, 12, 18, etc. months earlier, fly about the solar system in an orbit very similar to the Earth's but inclined, and then fly by the Earth to arrive onto the targeted transfer type listed above. This strategy provides more launch windows for a given transfer type.

- Venus Flyby options. Many options exist that have the spacecraft descend to a Venus flyby prior to traveling to Mars. It requires less energy to get to Venus than to Mars, but it requires more transfer duration, a sensitive Venus flyby, and typically higher arrival velocities at Mars. One could theoretically combine a Venus flyby and an Earth flyby to reduce the Martian arrival velocity. These options can quickly become too complex and long-duration and therefore were not considered.

Table 1 compares these transfer types. There are some cases where a given transfer type varies enough to consider different areas of the trade space. Hence, there are two Type I transfers compared.

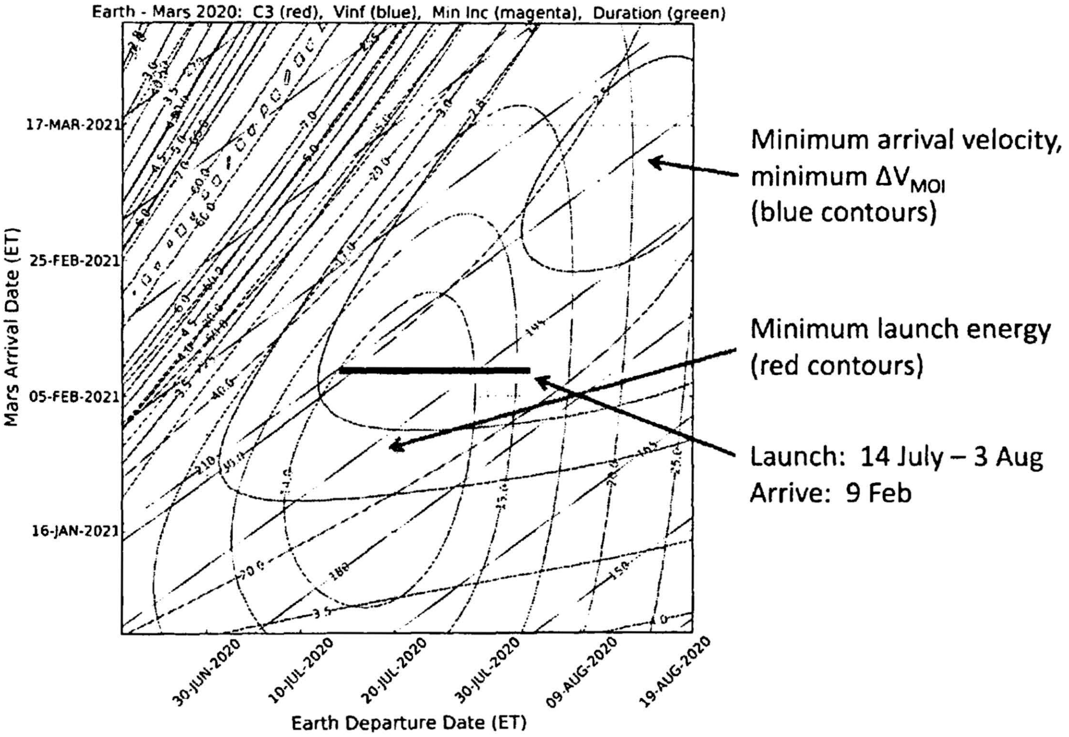
Table 1. The trade space of interplanetary cruise options for EMM; green is desirable, red is undesirable.

Type	Departure	Arrival	Duration	Launch C_3	Arrival V_∞	Notes
Type I	7/2020	2/2021	7 months	14 km^2/s^2	3.0 km/s	Selected
Type Ib	8/2020	2/2021	6 months	26 km^2/s^2	2.5 km/s	
Type II	5/2020	2/2021	9 months	26 km^2/s^2	2.4 km/s	
Type IIb	8/2020	10/2021	14 months	17 km^2/s^2	4.1 km/s	
Type III	11/2019	12/2021	25 months	10 km^2/s^2	4.7 km/s	
Type IIIb	12/2019	1/2022	25 months	45 km^2/s^2	3.3 km/s	
Type IV	11/2019	2/2022	27 months	10 km^2/s^2	2.7 km/s	
Earth Flyby I	1/2020	2/2021	13 months	14 km^2/s^2	3.0 km/s	Launch 6 mo earlier
Earth Flyby Ib	2/2020	2/2021	12 months	26 km^2/s^2	2.5 km/s	Launch 6 mo earlier

The selected interplanetary transfer, the Type I indicated in Table 1, balances the needs of the project with the technical merits of that transfer. It is a transfer that does not spend an excessive amount of time in space, permits the project to have more time to develop and integrate the spacecraft system, and it requires reasonably low launch and arrival velocities. It also arrives prior to the UAE's 50th anniversary.

Pork Chop Plot

Figure 5 illustrates the porkchop plot near and including the Type I transfer between Earth and Mars in 2020. The chart shows the interplanetary transfer data for each launch date and arrival date combination included in the axes. Contours are included that illustrate the transfer duration, the launch energy, the arrival velocity, and the inclination upon arrival at Mars. The minima indicated illustrate the range of desirable Type I transfers in this opportunity, focused on either launch energy, arrival velocity, or some combination. Finally, the launch and arrival period selected for EMM are indicated, including 21 launch opportunities. The launch period currently opens July 14, 2020 and closes August 3, 2020; all interplanetary transfers arrive at Mars on February 9th, 2021.



Minimum arrival velocity, minimum ΔV_{MOI} (blue contours)

Minimum launch energy (red contours)

Launch: 14 July – 3 Aug
Arrive: 9 Feb

Figure 5. The Type I Porkchop Plot.

Launch Trade

Almost every historical mission to Mars has flown a direct transfer: one that launches and transitions to a hyperbolic escaping trajectory within hours. Some scenarios have been flown by which the launch vehicle does not stop and coast until the spacecraft has reached its interplanetary velocity. Most recent missions involve a coast arc in orbit about Earth, such that the launch vehicle reaches orbit, pauses in one or more parking orbits for a matter of minutes to hours, and then performs the final maneuver to reach the interplanetary departure. The ISRO Mars Orbiter Mission is an exception: its launch vehicle placed the observatory in an orbit about Earth. Then, over the course of weeks, the spacecraft boosted its orbit into ever-higher orbits about Earth before performing its final maneuver to depart the Earth. This option is distinctly different because it does not involve the launch vehicle's upper stage. This option is referred to as the Phased Departure, the departure that uses Earth Phasing Orbits. Figure 6 illustrates the different options.

A major trade study was conducted to determine if it would be better to implement a conventional Direct Departure or to implement a Phased Departure. The Phased Departure requires a far more capable spacecraft, but it provides the largest launch period, and saves fuel in the entire system. It was determined that the additional complexity on the spacecraft side was not sufficiently offset by the benefits of the Phased Departure and a conventional Direct Departure was selected.

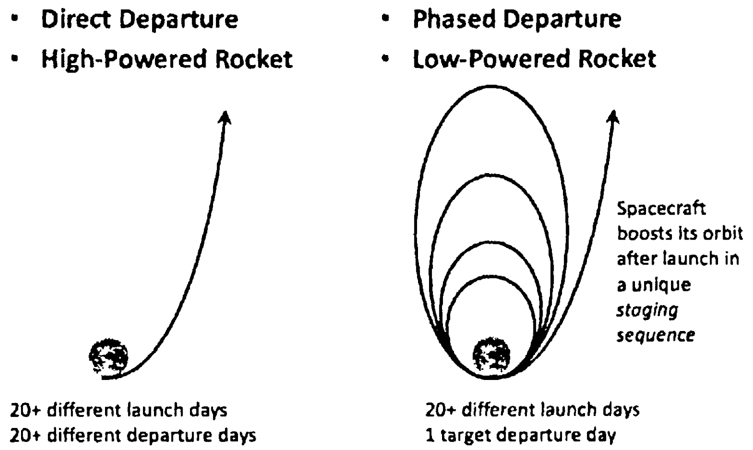


Figure 6. An illustration of the main features of the Direct Departure versus the Phased Departure.

MISSION DESIGN

This section describes the baseline mission design, as of the critical design review of the mission. The descriptions here begin with a discussion of the mission phases, and then provide details about each phase.

The Amal spacecraft will be launched from the Tanegashima launch site in Japan aboard an H-IIA launch vehicle. After a short coast in orbit about Earth, the H-IIA upper stage will boost the spacecraft onto its interplanetary departure.

The spacecraft spends approximately seven months cruising to Mars. It arrives at Mars and executes the Mars Orbit Insertion (MOI). This places the spacecraft into its Capture Orbit. The spacecraft remains in the Capture Orbit for approximately 40 days before transitioning to the Science Orbit. The Science Orbit is a very large orbit about Mars, requiring approximately 55 hours to traverse each orbit. The spacecraft executes its primary mission from this orbit over the course of one Martian year (687 Earth days, nearly two Earth years). Options exist for an extended mission since this orbit does not require fuel to maintain. When the mission is complete it will decommission in the same orbit and passively satisfy planetary protection.

Mission Phases

The EMM design includes eight mission phases during flight, including the following:

1. **Launch Phase**: Launch, which begins at the moment of liftoff and extends through spacecraft separation until the spacecraft executes its first command to point in a desired inertial direction.

2. **EOP Phase**: Early Operations, which extends from the end of the Launch Phase for approximately 30 days.

3. **Cruise Phase**: Interplanetary cruise, which extends from the end of EOP until approximately 30 days before the Mars Orbit Insertion maneuver.

4. **MOI Phase**: The phase dedicated to the Mars Orbit Insertion, which starts 30 days before MOI and extends approximately two days after MOI.

5. **Transition to Science Phase**: This phase begins with the spacecraft in a stable capture orbit, at which point the spacecraft begins commissioning in orbit about Mars. The Transition Phase includes three maneuvers to transition the observatory into its primary science orbit. This phase ends approximately 75 days after MOI.
6. **Science Phase**: The primary science mission.
7. **Extended Mission Phase**: One or more extended missions, with an undetermined end date.
8. **Decommissioning Phase**: The phase dedicated to passifying the spacecraft and ensuring that it satisfies planetary protection.

Launch

Mitsubishi Heavy Industries (MHI) operates the H-IIA launch vehicle for the Japanese Space Agency, JAXA. The vehicle's flight legacy includes ~30 successful launches since its inaugural flight in 2001. The H-IIA launch vehicle is integrated and launched from the Tanegashima Space Center in Tanegashima Island, located at the southwest of Japan.

The H2A202 launch vehicle configuration is comprised of an LE-7A 1st stage engine with two SRB-As, an LE-5B-2 2nd stage engine, and a 4S fairing.

The first stage consists of the high performance cryogenic LE-7A engine, engine section, LH_2 tank, center body section, LOX tank and interstage section. The LE-7A engine produces 1100kN of thrust using liquid hydrogen (LH_2) and liquid oxygen (LOX) as propellant. Two solid rocket boosters (SRB-A) are attached to the first stage in order to augment the total thrust during the first 100 seconds of the ascent phase. The motor case of the SRB-A is monolithic and made of filament winding composite material (CFRP). Additionally, electromechanical thrust vector control (TVC) system for gimbaling the nozzle is applied.

The second stage consists of the highly-reliable cryogenic LE-5B engine, LH_2 tank, LOX tank, and avionics system installed on the equipment panel. The LE-5B engine, which produces 137kN of thrust using liquid hydrogen (LH_2) and liquid oxygen (LOX) as propellant, has a multi-restart capability to meet various mission requirements. Attitude control is performed using electromechanical actuators of the LE-5B engine and the hydrazine gas-jet reaction control system (RCS). The RCS is used for attitude control and propellant settling of the second stage before and after the spacecraft separation.

Figure 8 illustrates the launch period for the mission. It opens on July 14, 2020 when the spacecraft fuel requirements drop within the allocated ΔV budget; it closes on August 3, 2020 when the launch vehicle's capabilities are exceeded for a 1500-kg payload.

The launch targets include a bias in order to satisfy planetary protection requirements. The upper stage of the launch vehicle will not have been built in an ISO Level 8 cleanroom facility. Therefore, EMM must demonstrate that the probability that the upper stage will impact Mars is below 0.01% within 50 years. This demonstration is provided in the EMM Planetary Protection Implementation Plan, which will be the subject of a technical paper in the near future. Once deployed, the spacecraft must demonstrate that its probability of impact with Mars is below 1% at all times for 20 years and below 5% for the subsequent 30 years.

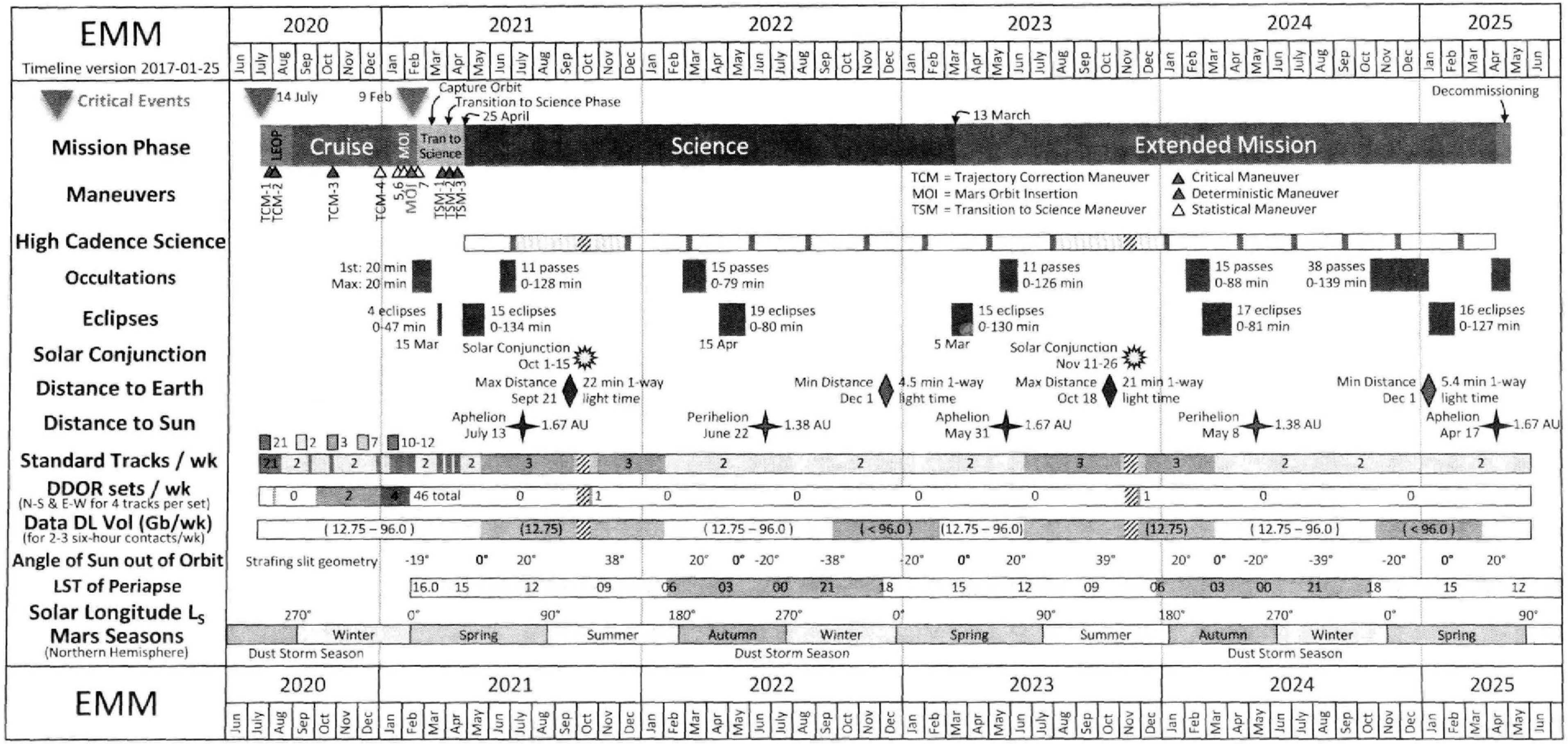


Figure 7. The EMM timeline for a launch on July 14, using the design as of 25-January-2017.

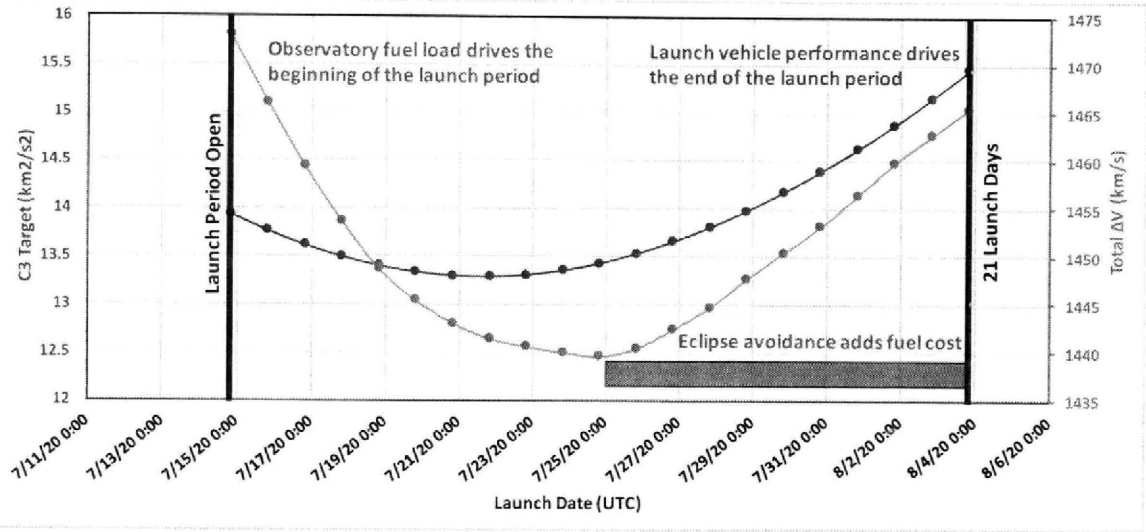


Figure 8. The EMM Launch Period and its constraints.

Interplanetary Cruise

The interplanetary cruise is a Type I transfer, requiring only seven months to travel from Earth to Mars. The launch energy and arrival velocity are balanced to support the mission design. Figure 9 illustrates the cruise, with the planets shown at the launch and at the Mars arrival of the cruise.

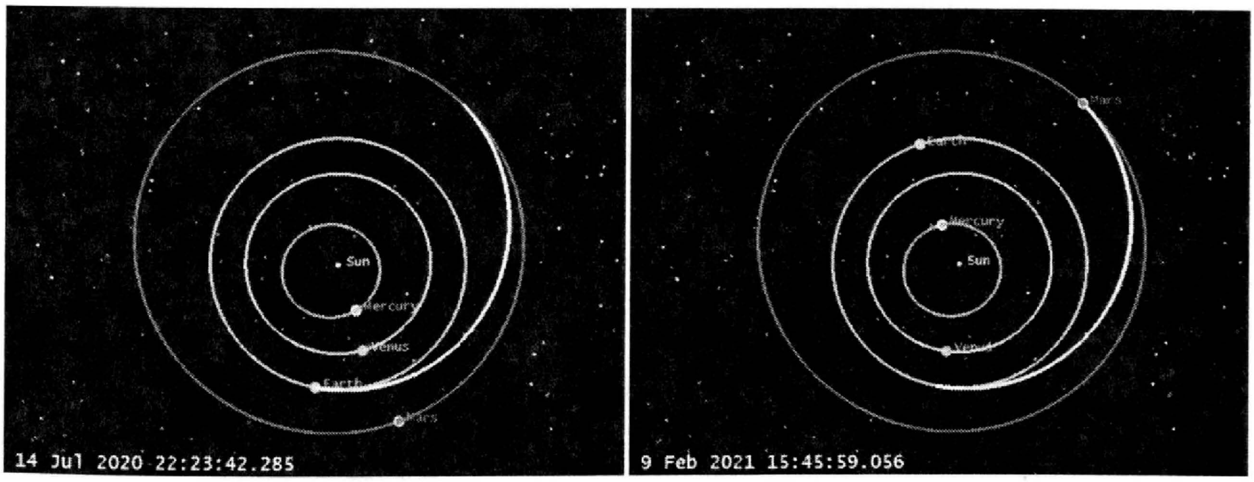


Figure 9. EMM's interplanetary cruise, with planets shown at the time of launch (left) and at the Mars arrival (right).

The launch and first two trajectory correction maneuvers (TCMs) are biased to satisfy planetary protection requirements. A total of six TCMs are planned in the interplanetary cruise:

- **TCM-1** is scheduled for 12 days after launch. It is a 10 m/s maneuver that will calibrate the main engines and remove a significant part of the launch bias.
- **TCM-2** is scheduled for 20 days after launch. It will remove the majority of the remainder of the launch bias, but will retain a small bias itself for planetary protection reasons.
- **TCM-3** is scheduled on a block schedule, which varies according to the launch day, but which

is approximately 100 days after launch. It will be the first maneuver to target the Mars Orbit Insertion corridor.

- **TCM-4** is scheduled for 40 days before MOI. It will clean up navigation and maneuver execution errors, targeting the MOI corridor.
- **TCM-5** is scheduled for 14 days before MOI. It is also a statistical maneuver to clean up the trajectory and target the MOI corridor.
- **TCM-6** is scheduled for 4 days before MOI. It is the final opportunity to adjust the trajectory prior to arriving at Mars.

All TCMs are executed on the main engines. Maneuvers larger than 1 m/s use the accelerometers to target the maneuver's ΔV with timer cutoff backups. Small maneuvers are open-loop maneuvers that use a timer to control the length of the maneuver. Any ΔV below 2 cm/s will be canceled.

The total TCM ΔV budget is 30 m/s; navigation Monte Carlo analyses demonstrate that well over 99 percent of scenarios fit within this budget and satisfy planetary protection requirements. These analyses will be presented in a later paper.

Mars Orbit Insertion

The Mars Orbit Insertion (MOI) is a $\sim$30-minute maneuver, performed on the main engines. It is the only critical maneuver performed by the main engines, so substantial care has been given to assure that it has the highest probability of performing successfully. The final month of the cruise – the MOI moratorium – is devoted to ensuring the maneuver occurs successfully. The maneuver is designed many weeks prior to arriving at Mars and tested thoroughly. The only parameter that may be changed by the navigation team as Amal approaches Mars is the maneuver's start time. This adjustment removes errors caused by the onboard clock and by the arrival hyperbola's periapsis passage timing.

The target capture orbit has a periapse altitude of 500 km and an orbital period of 40 hours. The orientation and plane of the orbit are free parameters, optimized to minimize the total ΔV in the mission.

The MOI is designed to efficiently remove energy, transitioning the spacecraft from a hyperbola to an ellipse. The spacecraft begins thrusting in a particular inertial direction, which is nearly in the anti-velocity direction. The spacecraft rotates during the maneuver at a constant rate about an inertially-fixed axis. The axis of rotation is approximately aligned with the spacecraft's orbit normal vector. In this fashion, the spacecraft keeps the thrust vector approximately aligned with the anti-velocity direction using only a few parameters that may be stored in non-volatile memory.

The nominal MOI design is described in Table 2 for the open, middle, and close of the launch period. The B-Plane parameters are specified relative to Mars' pole vector. The $\hat{S}$ vector is aligned with the asymptotic approach velocity vector $\hat{V}_\infty$; the $\hat{T}$ vector is equal to the cross product of $\hat{S}$ and the Mars spin axis vector, $\hat{k}$; finally $\hat{R}$ is equal to $\hat{S} \times \hat{T}$. EMM targets a $B \cdot T$ value that places it into a prograde capture orbit and a $B \cdot R$ value that is negative, i.e., above the Martian equator. The designs provided here assume a worst-case initial mass of 1500 kg, an effective total thrust of 612.36 Newtons, and an Isp of 226.2 seconds. The total thrust assumes a 90% duty cycle for pitch and yaw control. The RCS system will maintain roll control, effectively dropping the mass slightly more during the maneuver.

Table 2. The nominal MOI design for the open, middle, and close of the launch period.

Parameter	July 14 Launch	July 24 Launch	August 3 Launch
Target $B \cdot T$	7415.6 km	7431.6 km	7315.0 km
Target $B \cdot R$	-2517.7 km	-3031.6 km	-3405.3 km
Altitude at Start	1205.3 km	1147.1 km	1160.2 km
True Anomaly at Start	298.12 deg	299.91 deg	300.70 deg
True Anomaly at End	47.90 deg	46.11 deg	46.56 deg
Rotation Rate	1.405 deg/min	1.399 deg/min	1.573 deg/min
Maneuver Duration	31.67 min	30.20 min	29.99 min
ΔV	958.65 m/s	903.83 m/s	896.15 m/s

The MOI is designed so early that it is impossible to perfectly predict where Amal will cross Mars' B-Plane. Therefore the nominal MOI is designed assuming that the spacecraft will arrive at Mars in the perfect location. In reality the MOI design will be executed on a different trajectory: one that pierces the B-Plane at some other location. The MOI B-Plane Corridor has been designed to include all regions of the B-Plane that produce successful missions, including expected maneuver execution and navigation uncertainty. Figure 10 illustrates the B-Plane corridor for the July 14th launch.

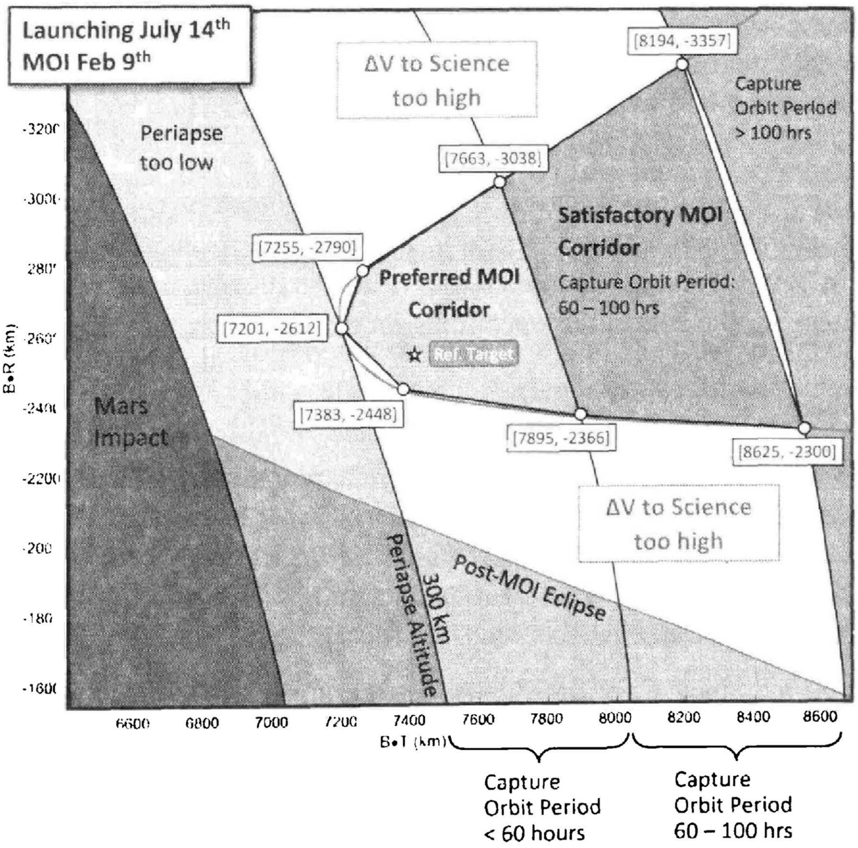


Figure 10. The MOI Corridor size and definition for a launch on July 14th.

The MOI Corridor's boundaries are defined as follows.

First, the spacecraft cannot perform MOI too low: at a critically low altitude its periapse altitude will be too low to satisfy planetary protection requirements. It has been determined that a post-MOI periapse altitude of 300 km is the minimum that will support planetary protection requirements, i.e., at that altitude atmospheric drag will be small enough to avoid fully entering the atmosphere within 50 years. At the lowest B-Plane arrival point, the spacecraft could enter a capture orbit whose orbital period is anywhere from 31 to 43 hours, given the current $\pm 3\sigma$ uncertainties in the maneuver execution.

Second, the spacecraft cannot perform MOI too high: at a critically high altitude, the resulting capture orbit's period would be too high and the mission would not satisfy planetary protection. The gravitational perturbations caused by the Sun's gravity produce a long-term oscillation; at the time of the MOI, the perturbations cause the periapse's altitude to drop. The nominal mission observes a drop of 50–100 km, which is acceptable. The periapse altitude drops enough to fully enter the atmosphere when the capture orbit has an orbital period just above 100 hours. The boundary of 100 hours has been determined to conservatively satisfy planetary protection. The boundary in Figure 10 corresponds to the outer edge of the B-Plane if a 3σ short burn is executed: the orbital period at the highest B-Plane arrival point could be anywhere from 60 to 100 hours, given the current $\pm 3\sigma$ uncertainties in the maneuver execution.

Third, the spacecraft cannot perform MOI too far North or South than the nominal arrival point. The additional plane changes that would be required to reach the target science orbit would exceed the spacecraft's total ΔV budget.

Finally, it is of interest to avoid passing through Mars' shadow on the first orbit at Mars, since it is possible that the first eclipse passage sends the spacecraft to Safe Mode. The MOI Corridor for a launch on July 14 does not overlap regions that would enter Mars' shadow, but the MOI Corridors for launches in the second half of the launch period do overlap. Thus, the Southern boundary is defined to avoid passing through Mars' shadow.

Despite having several constraints, the MOI Corridor is remarkably large, simplifying the challenges for the navigation team. It is preferred to target a point in the lower portion of the MOI Corridor (shaded in lighter green) to reduce risk, to make the mission more resilient to contingency scenarios, and to improve the concept of operations for the transition to science.

Transition to Science

The Transition Phase of the mission is designed to last approximately 75 days, including 40 days in the Capture Orbit. Three Transition to Science Maneuvers (TSMs) efficiently modify the orbit to place the spacecraft into the Science Orbit. The three TSMs' placement and targets have been optimized in the presence of maneuver execution uncertainty to reduce the 99th percentile for the total ΔV needed to navigate the sequence.

The Capture Orbit may have a periapse as low as 300 km or as high as 1300 km in altitude; its orbital period may be as low as 31 hours or as high as 100 hours. The transition strategy is nearly identical for each scenario, though the resulting ΔV budget and science orbit injection accuracy varies.

The first transition to science maneuver, TSM-1, is performed near the apoapsis of an orbit approximately 40 days after MOI. Its primary purpose is to raise the periapsis to a value between

16,000 and 17,000 km in altitude, depending on the scenario; it also rotates the orbit and changes its inclination. The second maneuver, TSM-2, is performed near a subsequent apoapsis approximately 10 days later. It raises the periapsis to approximately 20,000 km and further rotates the orbit. The third maneuver, TSM-3, is performed near a subsequent periapsis approximately 10 days later. It modifies the apoapsis to target a value of 43,000 km in altitude and completes the rotation of the orbit. The mission then spends 15 days preparing for science before officially starting the science phase.

In the reference mission, with a 40-hour Capture Orbit, the first TSM is approximately 335 m/s, the second TSM is approximately 48 m/s, and the third TSM is approximately 38 m/s. With this sequence, TSM-2 is able to clean up the majority of the navigation errors incurred by TSM-1. The science orbit injection accuracy is largely a function of TSM-2 and TSM-3, both of which are relatively small. There are some scenarios, notably if the Capture Orbit is very large, that involve a larger TSM-3, though the execution errors are still acceptable. If TSM-1 is delayed, the total ΔV drops due to the J_2 effect, though the mission prefers to execute TSM-1 no later than 40 days after MOI as long as the mission is prepared to do so.

Science Phase

The target Science Orbit has a periapse altitude of 20,000 km, an apoapse altitude of 43,000 km, an orbital period of approximately 55 hours, an inclination of 25 degrees relative to Mars' pole, and an argument of periapsis of 177 degrees. The argument of periapsis is set such that it drifts through 180 degrees during the science phase, optimizing the science product. The right ascension of ascending node of the orbit is a free variable and is the only parameter that changes across the launch period.

The mission undergoes all variations in range and geometry expected from the Mars mission. Specific aspects of the mission that are tracked carefully include the angle between the orbit normal vector and the Sun, since that angle impacts how often the Sun is in the keep-out zone of the instruments during operations, the local solar time (LST) of the spacecraft's groundtrack, the LST of the spacecraft's periapsis, and the Mars Solar Orbit (MSO) coordinates of the spacecraft's groundtrack. Figure 7 illustrates the mission timeline and the progression of these parameters through the mission.

The concept of operations in the primary Science Phase of the mission involve the spacecraft slewing between a sun-point, charging attitude, and a science collection attitude. The observatory captures EMIRS and EXI observations approximately every 2.55 hours when available. This is interrupted by ground contacts, eclipses, and periods of time during which the Sun is too close to the boresight of the instruments to safely collect the observations. EMUS captures observations in different ways with different cadences; most observations are place in conjunction with an EXI and EMIRS observation to avoid inefficient slew patterns. The detailed descriptions of science products are outside of the scope of this paper. It suffices to say that this orbit with routine observations satisfies the needs of the investigations to collect global, diurnal maps of the Mars surface and atmosphere within short timeframes, routinely during an entire Martian year.

CONCLUSIONS

The mission design described in this paper supports a mission that launches from Japan onto an interplanetary transfer and maneuvers into a highly desirable science orbit to support global, diurnal, temporal observations of Mars. The mission design and navigation system satisfies all planetary protection requirements, given that the spacecraft is built in an ISO Level 8 clean room. This mission design places the Amal spacecraft into orbit about Mars well before the UAE's 50th anniversary.

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