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MARS 2020 MISSION DESIGN AND NAVIGATION OVERVIEW

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Following the exceptionally successful Mars Science Laboratory mission which placed the Curiosity rover in the interior of Gale Crater in August 2012, NASA will launch the next rover in the 2020 Earth to Mars opportunity arriving to the Red Planet in February 2021 to explore areas suspected of former habitability and look for evidence of past life. This paper details the mission and navigation requirements set by the Project and how the final mission design and navigation plan satisfies those requirements.

INTRODUCTION

The Mars 2020 (M2020) Project will address high-priority science goals for Mars exploration, including key questions about the potential for life on Mars. The mission will take the next step by not only seeking signs of habitable conditions on Mars in the ancient past but also searching for signs of past microbial life itself. The M2020 rover will feature a drill that can collect core samples of the most promising rocks and soils and set them aside in a cache on the surface of Mars for their potential return to Earth. The mission will also provide opportunities to gather knowledge and demonstrate technologies that address the challenges of future human expeditions to Mars including oxygen production from the Martian atmosphere, identification of other resources such as subsurface water, improvement of landing techniques, and characterization of the environmental conditions that could affect future astronauts living and working on Mars.[1,2]

On 11/19/18 and after a five-year search during which details of more than 60 candidate locations on Mars were scrutinized by the mission team and the planetary scientific community, NASA announced that Jezero Crater had been selected as the landing site for the M2020 rover. This site offers geologically rich terrain with landforms reaching as far back as 3.6 billion years old that could potentially answer important questions in planetary evolution and astrobiology. Jezero Crater is located on the western edge of Isidis

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Planitia, a giant impact basin just north of the Martian equator. Scientists believe that this crater, once home to an ancient river delta, could have collected and preserved ancient organic molecules and potential signs of microbial life from that water and sediments that flowed into the crater billions of years ago[3].

The M2020 Project will accomplish the above objectives by landing a single mobile science laboratory (i.e., a 'rover') on the surface of Mars. The M2020 project will use the proven design and technology developed for the Mars Science Laboratory (MSL) mission and rover (Curiosity) that arrived at Mars in August 2012. This is a key element of the M2020 flight system development planning; entire systems, and many elements of the rover system will be inherited from MSL without change. The M2020 flight system includes a cruise stage, an aeroshell (backshell, heatshield, and parachute system), a propulsive descent stage and key engineering subsystems and designs of the Curiosity rover. The M2020 cruise stage, aeroshell and descent stage systems will be build-to-print. A substantial portion of the M2020 rover subsystems will also be based on those of Curiosity and be build-to-print, with the most significant exceptions being the new payload elements, and the sample collection and caching system. Rover thermal / mechanical system and harness tailoring is expected to be necessary to accommodate these new elements.[4]

MISSION

Launch

The M2020 flight system will launch in the 2020 Earth to Mars Type 1 opportunity from the Eastern Test Range (ETR) at Cape Canaveral Air Force Station (CCAFS) in Florida on an Atlas V 541. The baseline 20-day launch period extends from July 17th through August 5th, 2020. The supplementary 10-day launch period immediately follows the baseline launch period and extends from August 6th, 2020 through August 15th, 2020. The supplementary launch period consist of dates with potential launch opportunities being analyzed for their possible integration into the existing baseline launch period. Viability of any of these dates depends on launch vehicle performance. Preliminary data indicate that some of these may have a finite launch window and may be integrated at a later time. All launch days have a constant arrival date of February 18th, 2021. Launch windows will not exceed 2 hours in duration. Two launch flight azimuths will be flown across the launch period to maximize launch vehicle performance while satisfying DSN coverage requirements. The Centaur first burn, which is the longer of the two Centaur upper stage firings, will inject the vehicle into a 90x137 nmi park orbit inclined at 34.6 deg (July 17th – July 23rd) or 29.2 deg (July 24th – August 12th). After coasting for 24 to 36 min, the Centaur/spacecraft stack will reach the proper position for the second Centaur burn to inject the spacecraft onto the desired departure trajectory. The launch window on any given day during the baseline launch period has a duration between 75 and 120 min. Launch windows are typically determined by launch vehicle performance and the required injection energy, but for M2020, shorter launch windows are constrained by the need of having continuous DSN coverage starting at Separation plus 5 minutes. The launch vehicle injection targets are specified as twice the hyperbolic injection energy per unit mass (C_3), declination of the launch asymptote (DLA), and right ascension of the launch asymptote (RLA) at the Targeting Interface Point (TIP), defined as Separation plus 4 min. The injected spacecraft mass is 4,147 kg. Propellant Margin (PM) defined as the additional burnable propellant beyond the Flight Performance Reserve (FPR), and Launch Vehicle Contingency (LVC), are used to create daily launch windows.

Interplanetary Cruise and Approach

During the 7-month interplanetary flight of the spacecraft, several major activities are planned including: up to six Trajectory Correction Maneuvers (TCMs) needed to target to the desired atmospheric entry aim point at Mars; checkout and maintenance of the spacecraft in its flight configuration; monitoring, characterization, and calibration of the spacecraft and payload subsystems; periodic attitude adjustments for power and telecommunications; navigation activities for determining and correcting the vehicle's flight path; and preparation for EDL and surface operations. Also, during cruise, solar array switching will be autonomously performed by the flight system. A plot of the heliocentric trajectory for the open of the launch period is shown in Figure 1.

The launch aimpoint targets are biased away from Mars for planetary protection in order to achieve a probability of less than 1.0×10^{-4} of the Centaur upper stage impacting Mars over the next 50 years (compliance during the first 50 years being a change from the MSL requirement but it is consistent with Planetary Protection requirements for the Mars InSight mission). All biased injection aimpoints are designed to target Jezero Crater shown in Figure 2. Planetary protection also requires that the probability of any anomaly causing impact of the M2020 spacecraft with Mars must be less than 1.0×10^{-2}. This is referred to as the non-nominal impact probability (NNIP) requirement. Normally, the deterministic ΔV to remove the injection bias and to perform retargeting is combined with the ΔV to correct launch vehicle injection dispersions. This is all used to generate the TCM-1 maneuver necessary to target the spacecraft to the desired Mars atmospheric entry aimpoint. In order to satisfy the non-nominal impact probability requirement for M2020 the aimpoint for TCM-1 and TCM-2 will be biased away from Mars (for MSL, the TCM-2 aimpoint was not biased because the calculated non-nominal impact probability during maneuver design did not violate the Planetary Protection requirements). During operations, it will be determined whether it is necessary to bias TCM-2 based on orbit determination (OD), probability of spacecraft failure (Q), and other relevant data. The Cruise phase TCMs are described in Table 1.

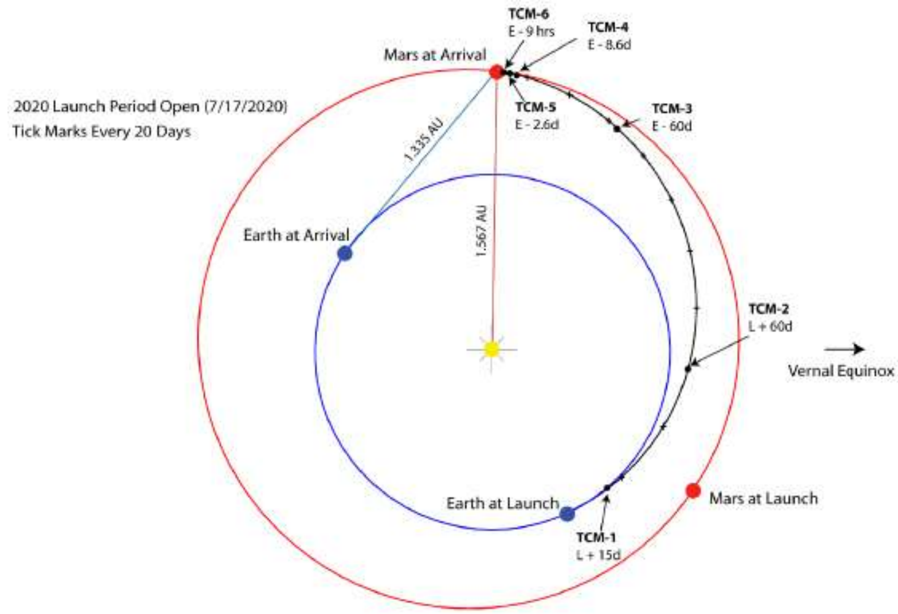

Figure 1. Interplanetary Trajectory for launch on 07/17/2020 (Launch Day 1)

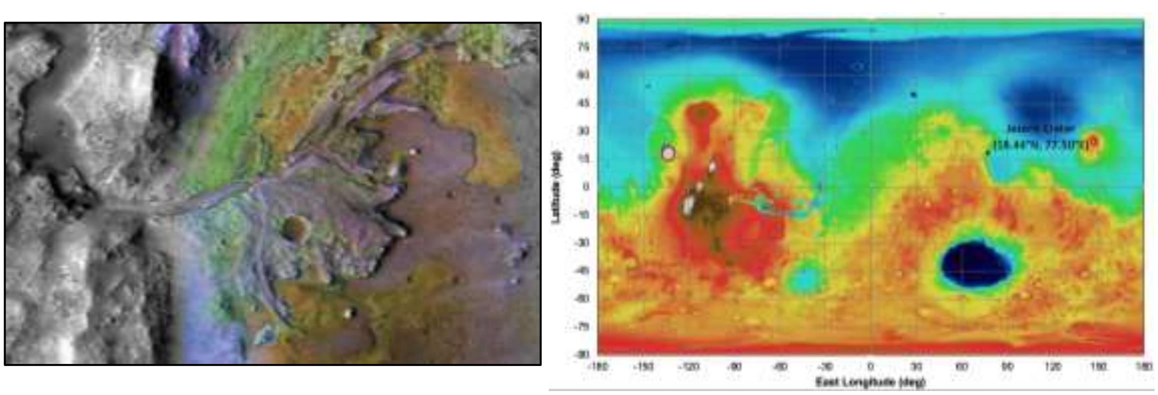

Figure 2. Landing Site Target – Jezero Crater

The Approach phase is defined to begin at 45 days prior to atmospheric entry (E-45 days) and ends when the spacecraft reaches the Mars atmospheric entry interface point, which corresponds to a Mars radius of 3,522.2 km. This mission phase is focused on preparations for Entry, Descent, and Landing (EDL) to ensure an accurate delivery to the required atmospheric entry point and that all EDL sequence parameters are properly loaded on the spacecraft. This means that, to the maximum extent possible, activities on the ground and on the spacecraft will be limited to those that support (1) accurate navigation; (2) preparation, testing, and uplink of the EDL sequence; and (3) final readiness of the operations teams. During this phase all activities that could compromise the spacecraft trajectory are minimized, and significant increases in DSN coverage and navigation data acquisition are used to improve the accuracy of trajectory solutions for TCMs 4, 5, 5X, and 6.

Approximately two weeks prior to atmospheric entry, the EDL initialization sequence is transmitted to the spacecraft. This sequence would run from 2 weeks before entry and consists of the commands necessary to initiate the EDL behavior, charge the rover secondary batteries, and preheat several EDL components. The EDL behavior is an autonomous flight software designed to control the spacecraft's actions during the critical events of EDL. Two commands initiate the EDL behavior at E-5 days. The first of these is a set of EDL timing parameters that were previously loaded on the spacecraft that define the epochs that the EDL behavior uses to determine when events occur. The second command initiates the EDL behavior and then execution begins after TCM-4. Three additional opportunities are planned to provide updates to the EDL parameters (but are not all necessarily used). These updates result from later data acquired from navigation's assessment of the trajectory. From an EDL perspective, the Approach phase is defined to end 5 days before entry, at which time the pre-entry segments start. The EDL initialization segment consists of the final approach sub-segment from E-5 days to E-30 min and the EDL start sub-segment from E-30 min to E-10 min, when Cruise Stage Separation occurs. The pre-entry segment of Approach encompasses a series of autonomously executed and ground-initiated activities required to prepare the spacecraft for Cruise Stage Separation (CSS) and EDL[4].

Table 1. TCM Profile

TCM	Time	Date	OD Data Cutoff	Description
TCM-1	L + 15d	Varies	L + 10d	Correct injection errors; remove all or part of injection bias for planetary protection; partially retarget to the desired landing site; aimpoint biased for planetary protection.
TCM-2	L + 60d	Varies	L + 55d	Correct TCM-1 errors; first possible opportunity to target to desired atmospheric entry aimpoint; vector-mode maneuver.
TCM-3	E - 60d	Dec 20, 2020	E - 65d	Correct TCM-2 errors; target to desired atmospheric entry aim-point; vector-mode maneuver.
TCM-4	E – 8.6d	Feb 10, 2021	E – 9.15d	Correct TCM-3 errors; vector-mode maneuver.
TCM-5	E – 2.6d	Feb 16, 2021	E – 3.15d	Correct TCM-4 errors; final entry targeting maneuver required to achieve EFPA delivery accuracy requirement; vector-mode maneuver.
TCM-5X	E – 1.6d	Feb 17, 2021	E – 2.15d	Contingency maneuver for failure to execute TCM-5; vector-mode maneuver.
TCM-6	E - 9h	Feb 18. 2021	E - 15h	Contingency maneuver; final opportunity for entry targeting; vector-mode maneuver.

Notes: Time measured from Launch (L) or Entry (E).

Entry, Descent, and Landing

The M2020 EDL system is based heavily on the successful MSL EDL architecture. Like MSL, the entry vehicle will enter the Mars atmosphere directly from its interplanetary trajectory, without first entering orbit about Mars. Before entry, the Cruise Heat Rejection System thermal fluid loop is vented and the cruise stage is jettisoned. The entry vehicle, consisting of the backshell, heat shield, descent stage and rover, performs a series of guided maneuvers to reduce the effects of atmospheric and aerodynamic uncertainties, thereby reducing the size of the landing ellipse as compared to missions with no active guidance. During this period, measurements of temperature, heat rate, and aeroshell recession are made by the Mars Entry, Descent and Landing Instrumentation (MEDLI2) suite. The entry phase is followed by parachute deployment, heatshield separation, and then powering on of the landing radar to detect the ground. Powered descent guidance will trigger the powered descent vehicle to separate from the parachute and backshell around 2.2 km above the surface, at which point the descent stage, using its Main Landing Engines (MLEs) will fly toward a selected safe target on the surface while slowing down the vehicle. Approximately 20 m above the surface the rover will separate from the descent stage and deploy its wheels, while being lowered via a set of bridles. Upon successful touchdown, the bridles and umbilical connecting the descent stage and the rover will be cut and the descent stage will throttle up its engines and fly away, eventually impacting the surface at a safe distance from the rover. Noteworthy changes to the EDL architecture for M2020 include the use of Terrain Relative Navigation (TRN) which enables the mission to land in more challenging terrain, as well as the inclusion of a range trigger for the parachute, which results in a smaller landing ellipse size[4].

Surface

Once the rover has safely landed the Surface phase begins. The first several sols will focus on commissioning the rover subsystems including critical rover deployments, rover health checks, and establishment of communication with Earth. Critical deployments will include the deployment of the high gain antenna, the deployment of the remote sensing mast (RSM) and the release of the launch lock constraints on the arm. After the remote sensing mast has been deployed, the rover will image the landing site. These data, along with rover health telemetry, will have priority for data return. Instrument health checks will be included in the early surface ops activities. In addition to rover commissioning, there will be an extended period during which a series of first-time activities are performed, and extra cautions are taken in the planning of these events. Drive-away, no earlier than sol 5, begins the more traditional surface mission. The surface mission will consist of the acquisition of science data and traverses between varied areas of interest. The primary mission will end at landing plus 836 sols[4]. A Mars Helicopter is expected to travel with the M2020 rover mission. Its 30-day flight test campaign will include up to five flights of incrementally farther flight distances, up to a few hundred meters, and longer durations as long as 90 seconds[5].

SPACECRAFT

The flight system consists of four major physical elements: the cruise stage, the aeroshell (heat shield and backshell), the descent stage, and the rover with new science instruments, and Sample Caching System with associated planetary protection requirements. The Entry, Descent, and Landing (EDL) system includes the aeroshell and descent stage. The total launch mass allocation is 4,147 kg. Figure 3 shows an expanded view of the M2020 Flight System showing the key flight system changes with respect to the MSL-heritage system.

Figure 3. M2020 Flight System

Cruise Stage

Following the launch of the M2020 flight system, the spacecraft is separated from the launch vehicle, and the cruise stage serves as the mechanism for the interplanetary portion of the journey, though cruise utilizes the rover compute element. During the 7-month trip to Mars, the cruise stage will perform up to six trajectory correction maneuvers, provide power, and dissipate heat generated on board the flight system. Throughout cruise, the flight system is spin-stabilized at 2.0 rpm. The cruise stage provides the following functionality over the Cruise and Approach phases of the mission: power generation and switching, attitude determination and control, trajectory control, and telecommunications. The avionics, including the flight computer that contains the attitude determination and control algorithms and much of the power conditioning hardware that is used during cruise and approach, is contained within the rover. The primary telecommunications hardware used during cruise and approach is in the descent stage[4].

Cruise Propulsion Subsystem

The propulsion system is used to maintain cruise spin rate, control spacecraft attitude, and impart ΔV for trajectory correction maneuvers (TCMs). M2020 uses a monopropellant hydrazine propellant system designed for spinning operations. Eight 4.5 N thrusters are mounted in two thruster clusters such that there are coupled thruster pairs allowing both axial and lateral maneuvers. Two 19-inch diameter fuel tanks hold 70 kg of propellant for the Attitude Control System (ACS) and TCMs during the cruise phase. The tanks contain a diaphragm and the propellant is pressurized within the tank and operated in blow down mode throughout cruise[4].

Cruise Power and Thermal Subsystems

During the Cruise and Approach phases, the spacecraft is powered by solar arrays mounted in an annulus on the cruise stage. The array is comprised of 12 partitioned electrical segments mounted on 6 physical panels that are switched automatically (in hardware) based on power bus control voltage, allowing regulation of the bus voltage across the entire span of load cases, sun angles, and solar ranges. With all strings online, the 12.8-m^2 array (active area) provides over 1,165 Watts at up to 30° off-Sun pointing at Mars arrival. During cruise the spacecraft relies on power from both the solar arrays and the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) onboard the rover. The power bus is regulated by a linear shunt which dumps excess power into resistive heaters on the backside of the solar array substrate. Thermal considerations for M2020 cruise are greater than typical Mars missions due to the incorporation of the MMRTG, used to power the rover on the Martian surface. The cruise Heat Rejection System (HRS) consists of a large ring of 10 radiators mounted to the outside of the cruise stage that pumps around the cruise electronics, by the descent stage avionics cooling plate, and finally to the Rover Avionics Mounting Plate (RAMP) and MMRTG before returning to the HRS radiators. The cruise shunt radiator consists of heaters mounted on the back of the solar array's substrate and is capable of radiating ~800 W.

Cruise Telecom Subsystem

During the Cruise phase, the primary telecom subsystem consists of two X-band antennas, the Parachute Low-Gain Antenna (PLGA) and Medium-Gain Antenna (MGA), fed by the descent stage SDST (Small Deep Space Transponder) and amplified by a 100-W Traveling Wave Tube Amplifier (TWTA) mounted in the descent stage. The rover SDST-SSPA (Solid State Power Amplifier) provides a redundant X-band link during cruise, used in the event of a failure of the descent stage SDST or TWTA, but with significantly degraded performance, and likely requires the use of 70-m DSN stations during later cruise. The PLGA is mounted on top of the parachute cone assembly, which is visible through the center of the cruise stage. During cruise, as the Earth range increases, the ground will command a switch from the PLGA to the MGA (approximately 90 days after launch). Although the MGA requires more restrictive pointing with respect to the Earth, it provides significantly higher data rates. The telecom system provides data for ranging and Delta-Differential One-Way Ranging (ΔDOR) as well as spacecraft telemetry data from the engineering subsystems and payload[4].

Cruise Guidance and Control System

The M2020 Cruise Guidance and Control Subsystem makes extensive use of heritage hardware and flight software algorithms from the Mars Exploration Rovers (MER) and Mars Pathfinder (MPF) missions. Three-axis inertial attitude and spin rate are determined onboard in real-time using an internally redundant star scanner and one of two 4-head digital Sun sensors. The attitude control sensors on the cruise stage consist of a 'V-slit' star scanner with the FOV canted down 115° from the -Z-axis and two Digital Sun Sensor Assemblies (DSA). Each DSA consists of a Digital Sun Sensor Electronics box (DSE) and 4 Digital Sun-sensor Heads (DSH). One DSH is mounted pointing in the -Z direction while the other three are oriented looking radially outward 105° from the -Z- axis. Turns are performed by firing coupled pairs of 'precession' thrusters. Precisely timed pulses are fired twice per spacecraft revolution to generate a torque that precesses the spin axis of the spacecraft in the desired inertial direction. Axial burns fire a pair of thrusters (one from each cluster) continuously. Axial burns impart ΔV along the spin axis of the spacecraft in either the +Z or -Z direction. Lateral burns are used to impart ΔV to the spacecraft in a direction roughly perpendicular to the spin axis. In a lateral burn, thruster pulses are fired alternately from each cluster (with all four thrusters fired simultaneously) as it rotates through the plane of the desired inertial ΔV. One thruster in each cluster is given a somewhat shorter pulse time than the other three so that the effective thrust points through the spacecraft center of mass. Lateral burns can achieve a ΔV at any inertial azimuth in a ~102° cone about the -Z-axis[4].

Entry, Descent, and Landing (EDL) System

For MSL, the descent phase began at supersonic parachute deploy when the desired navigated velocity was reached. For M2020, the deployment of the parachute will be based upon "range to the target" rather than "navigated velocity". This is referred to as "range trigger" for supersonic parachute deployment. "Range Trigger" enables a more accurate landing capability (smaller landing ellipse size than was possible for MSL). While decelerating on the parachute, the system will prepare the propulsion subsystem for powered deceleration, separate the heat shield, and begin using radar to acquire a landing solution. Stowed at the top of the backshell is a Viking heritage parachute scaled up to 21.5 m in diameter to accommodate the significantly heavier mass of the M2020 system. After these events, the descent stage and rover separate from the backshell. Like MSL, the remainder of EDL is an entirely powered, throttleable, propulsive descent, greatly different from the MPF and MER missions. The eight descent stage Mars Lander Engines (MLEs) will first reduce the descent rate and null any horizontal velocity. Once reaching a point approximately 20 m above the ground, the rover will separate from the descent stage, but will remain connected via the Bridle, Umbilical, and Descent rate limiter (BUD), consisting of three load-bearing tethers and an electrical umbilical. These tethers and umbilical are paid out from a spool by a mechanism that limits the relative separation rate until the tethers have reached their full deployment length. While the rover is slowly being lowered, the mobility system is deployed. This is essentially the surface configuration of the rover mobility system. When touchdown is sensed, the bridle connecting the rover and descent stage is severed, and the descent stage flyaway begins to prevent the descent stage from impacting the rover. Once the rover has landed, from a mobility perspective, it is ready to begin traversing the Martian surface[4].

REQUIREMENTS

The key and driving requirements for mission and navigation design are listed below:

The launch/arrival strategy shall…

Launch/Arrival Strategy

- … be consistent with a total launch mass of less than or equal to 4,147 kg.
- … have trajectories with entry velocities between 5.2 km/s and 5.6 km/s atmosphere relative.

TCM ΔV

- … require a set of TCMs whose total implemented propellant usage is not greater than 45 kg.

EDL Coverage

- … deliver the spacecraft to Mars with allowance for pre-launch selection of alternative EDL coverage methods (relay or DTE) from the FS during Entry, Descent, and Landing, from atmospheric entry through landing plus one minute

Atmospheric Entry Delivery/Knowledge Accuracies

- … deliver the FS entry body to the specified entry conditions with an inertial entry flight path angle error of less than or equal to 0.2 deg (3-sigma)
- … deliver the FS entry body to the reference entry point within 5 km (3-sigma) in the cross-track direction.
- … initialize the FS with an inertial state vector at the entry epoch with an accuracy of 2.8 km in position and 2.0 m/s in velocity for all trajectories in the Mars centered inertial frame (3-sigma).

Planetary Protection

- … be consistent with launch targets which bias the injection aimpoint such that the probability of Mars impact by the launch vehicle upper stage is less than 1.0×10^{-4} for 50 years after launch.
- … have trajectories with probability of non-nominal impact of Mars due to failure during the Cruise and Approach phases that shall not exceed 1.0×10^{-2}.

MISSION DESIGN

Launch/Arrival Strategy

The M2020 baseline 20-day launch period extends from July 17th through August 5th, 2020. The supplementary 10-day launch period extends from August 6th, 2020 through August 15th, 2020. Every launch date has a constant arrival date of February 18th, 2021. The launch/arrival strategy (see Figure 4) is designed to maximize launch vehicle performance and deliver the flight system to the Martian atmosphere with entry velocities between 5.2 km/s and 5.6 km/s, while allowing for EDL communication paths via orbiter relay or Direct-To-Earth (DTE) during Entry, Descent, and Landing (EDL), from atmospheric entry through landing plus one minute. It is highly desired to have at least two EDL communication paths should an anomaly occur during this critical event. The Mars Reconnaissance Orbiter (MRO) which successfully recorded open loop data during the Mars Science Laboratory (MSL) EDL event will again be positioned in an optimal geometry prior to the arrival of the vehicle to capture the M2020 Ultra-High Frequency (UHF) signal from a Local Mean Solar Time (LMST) of 3:15 PM. The X-band DTE link adds robustness to the EDL communication strategy; however, X-band semaphores do not contain telemetry data and are likely to be insufficient to fully reconstruct most EDL fault scenarios. In the 2020 Earth-to-Mars opportunity, later arrival dates favor DTE communications; hence, the launch/arrival strategy has the latest arrival date possible to extend DTE communications while preserving the required launch vehicle performance for a minimum of 20 continuous launch days. The launch/arrival strategy was selected to maximize DTE communications so DTE coverage is available from entry through some time after heatshield separation. This makes EDL communications via an orbiter relay critical since that path is the only means to obtain EDL data. In addition to MRO, in October 2017, NASA confirmed that the Mars Atmosphere and Volatile Evolution mission (MAVEN) orbiter will also be positioned to provide EDL relay communications adding robustness to the EDL communications baseline. MAVEN executed an inclination change maneuver in July 2018 to change the precession of the orbital plane to achieve the proper geometry to support the M2020 EDL event in February of 2021. The launch/arrival strategy figure also shows the regions of full (visibility from Entry to landing plus 1 minute) MRO and full DTE.

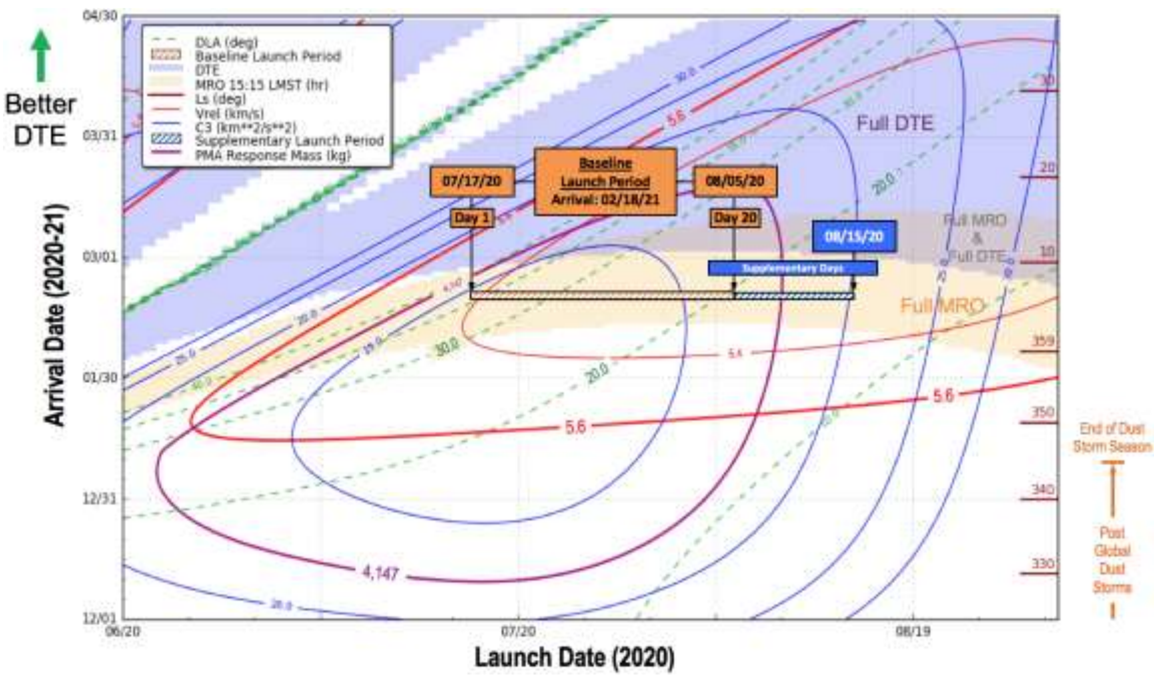

Figure 4. Launch/Arrival Strategy

Launch Period Characteristics

The launch vehicle targets represent the conditions of the osculating departure at the Targeting Interface Point (TIP) expressed in an Earth-center, inertial, Earth Mean Equator and Equinox of J2000 (EME2000) coordinate system. These Earth-relative target conditions are defined to occur 4 min after Separation and are shown in Table 2. Even though the table shows C_3, DLA, and RLA targets at open, middle, and close of the launch window, corresponding launch polynomials for each of these targets using time in minutes measured from the optimal launch time as the independent variable were delivered to the launch vehicle contractor[6]. The maximum C_3 occurs at the close of the launch period, whereas the maximum DLA occurs at the open of the launch period. Two different 90x137 nmi park orbits will be flown in order to maximize launch vehicle performance. Launch days 1-7 will launch into an inclination of 34.6 deg whereas launch days 8-30 will use a 29.2 deg park orbit inclination. In order to ensure continuous communications with the spacecraft starting at Separation plus 5 min, some daily launch windows will be skewed from the optimal launch time.

Table 2. Launch Targets and Arrival Characteristics

Earth Centered EME2000 Coordinates (C_3, DLA, RLA) at TIP										
Launch Day	Launch Date (2020)	C_3 (km^2/s^2)			DLA (deg)			RLA (deg)		
		Open	Middle	Close	Open	Middle	Close	Open	Middle	Close
1	07/17	14.4773	14.4648	14.4521	35.3179	35.2601	35.2064	13.9562	13.9571	13.9593
2	07/18	14.2770	14.2659	14.2551	34.2944	34.2374	34.1852	13.7032	13.7018	13.7018
3	07/19	14.1116	14.1019	14.0927	33.2773	33.2222	33.1728	13.4078	13.4044	13.4015
4	07/20	13.9823	13.9746	13.9672	32.2731	32.2209	32.1750	13.0764	13.0714	13.0663
5	07/21	13.8907	13.8848	13.8793	31.2939	31.2444	31.2015	12.7177	12.7107	12.7041
6	07/22	13.8354	13.8310	13.8273	30.3369	30.2898	30.2494	12.3394	12.3304	12.3218
7	07/23	13.8150	13.8121	13.8102	29.4057	29.3601	29.3218	11.9489	11.9383	11.9280
8	07/24	13.8342	13.8321	13.8304	28.5968	28.5510	28.5096	11.5672	11.5579	11.5510
9	07/25	13.8755	13.8745	13.8743	27.7118	27.6669	27.6271	11.1683	11.1573	11.1495
10	07/26	13.9458	13.9459	13.9471	26.8454	26.8019	26.7640	10.7697	10.7574	10.7486
11	07/27	14.0435	14.0451	14.0479	25.9956	25.9544	25.9192	10.3720	10.3591	10.3506
12	07/28	14.1674	14.1702	14.1744	25.1733	25.1344	25.1015	9.9794	9.9658	9.9566
13	07/29	14.3155	14.3197	14.3251	24.3783	24.3414	24.3105	9.5920	9.5778	9.5682
14	07/30	14.4866	14.4922	14.4988	23.6096	23.5747	23.5457	9.2092	9.1951	9.1852
15	07/31	14.6801	14.6868	14.6944	22.8666	22.8335	22.8062	8.8316	8.8167	8.8063
16	08/01	14.8951	14.9031	14.9118	22.1486	22.1172	22.0915	8.4574	8.4425	8.4318
17	08/02	15.1314	15.1403	15.1503	21.4582	21.4277	21.4033	8.0881	8.0728	8.0615
18	08/03	15.3906	15.4005	15.4117	20.7904	20.7614	20.7386	7.7206	7.7048	7.6934
19	08/04	15.6721	15.6829	15.6952	20.1538	20.1260	20.1043	7.3551	7.3390	7.3267
20	08/05	15.9780	15.9898	16.0032	19.5502	19.5243	19.5044	6.9813	6.9643	6.9506
21	08/06	16.3068	16.3190	16.3319	18.9786	18.9569	18.9391	6.5653	6.5469	6.5312
22	08/07	16.6496	16.6614	16.6743	18.3675	18.3443	18.3241	6.0779	6.0598	6.0459
23	08/08	17.0236	17.0373	17.0504	17.6585	17.6355	17.6182	5.6668	5.6534	5.6450
24	08/09	17.4408	17.4545	17.4671	17.0026	16.9845	16.9712	5.3520	5.3407	5.3331
25	08/10	17.8921	17.9054	17.9191	16.4070	16.3925	16.3803	5.0491	5.0391	5.0317
26	08/11	18.3761	18.3888	18.4015	15.8444	15.8325	15.8223	4.7462	4.7376	4.7305
27	08/12	18.8943	18.9061	18.9178	15.3038	15.2942	15.2857	4.4480	4.4409	4.4347
28	08/13	19.4468	19.4593	19.4718	14.7834	14.7742	14.7660	4.1605	4.1535	4.1476
29	08/14	20.0373	20.0507	20.0640	14.2804	14.2716	14.2637	3.8857	3.8789	3.8732
30	08/15	20.6679	20.6821	20.6963	13.7947	13.7863	13.7787	3.6263	3.6198	3.6145

EDL Coverage

The mission design for M2020 enables full EDL communications coverage from MRO and MAVEN for all launch dates under consideration. The nominal plan for M2020 is DTE coverage using multiple-frequency-shift keying (MFSK) tones sent by the entry system and this will be considered the primary source of information from cruise stage separation to entry. Dual MRO and MAVEN UHF relay coverage (recorded telemetry from the entry system) will be the primary telecom link from atmospheric entry to rover landing. DTE from entry to landing extends through at least heat shield separation. It is important to note that the MRO and MAVEN orbiters are not capable of bent-pipe relay; instead, the orbiters will record M2020 telemetry during EDL and return it as soon as possible. The current plan is to configure MRO to record in closed loop and MAVEN in open loop. For MSL, ODY was capable of bent-pipe communications and provided near real-time telemetry during EDL but the current location of its orbital plane (6:45 PM LMST) is not compatible with the M2020 arrival geometry. Unless the MRO spacecraft is modified to enable bent-pipe communications, this feature of having MSL-like real-time communications is not expected to be available for M2020; although, latencies will be reduced by having one of the orbiters record in close loop. The UHF link will not allow all faults to be detected, particularly if the failure interferes with the spacecraft's ability to maintain the link. X-band semaphores will be used to provide information on the major events or event anomalies during EDL. Figure 5 shows the different communications paths and expected latencies during EDL.

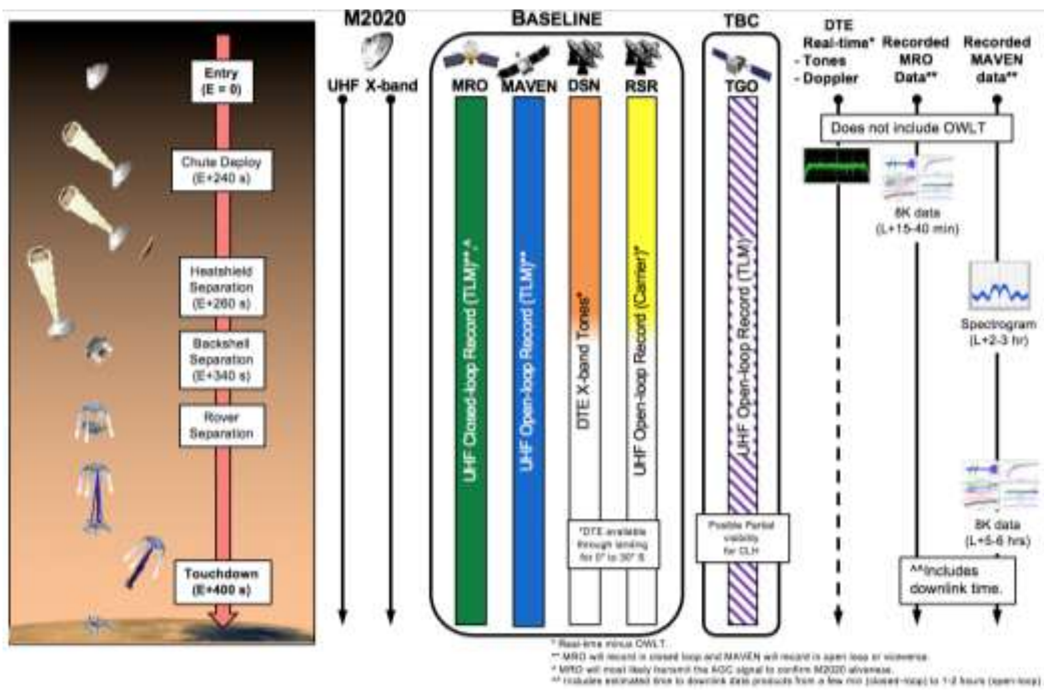

Figure 5. Data Recorded during EDL

NAVIGATION

Tracking Data

The baseline radiometric data types that will be used for M2020 orbit determination are two-way coherent Doppler, two-way ranging, and ΔDOR measurements generated by the DSN X-band tracking system. Doppler and range are derived from a coherent radio link between the spacecraft and a receiver at a DSN ground station. In the case of ΔDOR, a radio signal from a quasar will also be used to obtain the measurements. For about the first 90 days of flight, the spacecraft will utilize the PLGA on the cruise stage. After that time, the spacecraft will utilize the cruise MGA. The PLGA to MGA transition activity will occur earlier in cruise for launches in the later part of the launch period. The baseline coverage includes ΔVLBI measurements (ΔDOR) during the Cruise and Approach phases. The ΔDOR data type has been incorporated into the navigation baseline in order to satisfy the entry delivery accuracy requirement. The baseline navigation tracking coverage assumed for this analysis is shown in Table 3.[7]

Table 3. DSN Navigation Tracking Schedule

Relative Dates		Calendar Dates		Doppler/ Range Schedule	DDOR Schedule
Start	End	Start	End		
Launch	Launch + 30d	07/17/20	08/16/20	Continuous	None
Launch + 31d	E – 67d	08/17/20	12/13/20	5 8-hr passes per week	1 session per week
E – 66d	E - 45 d	12/14/20	01/04/20	5 8-hr passes per week	2 sessions per week
E – 44 d	E – 28 d	01/05/21	01/21/21	Continuous	2 sessions per week
E – 27 d	Entry	01/22/21	02/18/21	Continuous	2 sessions per day

ACS/NAV Calibration

The objective of the ACS/NAV calibration is to characterize the residual translational ΔV produced by spacecraft angular-momentum turns. A spacecraft turn uses pairs of thrusters firing in opposite directions, so it nominally produces zero net ΔV, but because the thrusters in general are not perfectly balanced, a small net ΔV will be produced. The residual ΔV for ACS turns plays a role in the propagation of the covariance for orbit predictions, since every one to two weeks a turn will be needed during late cruise and approach in order to execute the attitude maintenance strategy. In the orbit determination baseline, a conservative estimate of the residual ΔV error is used for the covariance propagation. Therefore, characterizing the residual ΔV will lead to a more accurate, and hopefully smaller, orbit prediction covariance. The ACS/NAV calibration consists of two identical sets of four 4.5 deg turns that are representative of the turns to be performed during late cruise and approach. During these turns, 2-way Doppler data are collected and used as observations to measure the net ΔV in the line of sight. The spacecraft attitude for each turn has been selected such that a complete reconstruction of the ACS residual ΔV vector is possible, considering that Doppler data only provides a measurement of the ΔV component along the line of sight.[7]

Propulsive Maneuver Implementation Modes and Maneuver Execution Accuracy

TCMs can be performed at the nominal cruise attitude without turning the spacecraft, or the spacecraft can turn to a specified attitude to execute the maneuver. Performing the maneuver without changing the spacecraft attitude corresponds to a vector mode implementation, so called because the desired ΔV is accomplished by a combination of axial and lateral burns such that the vector sum of those components produces the desired ΔV. If the maneuver is performed with a spacecraft turn, either a vector mode implementation can be used, or the desired ΔV can be accomplished with a purely axial or lateral burn. Because M2020 is a spinning spacecraft, lateral burns are accomplished by firing all four thrusters in each thruster cluster once per spacecraft revolution for a specified number of revolutions. Axial burns are accomplished by firing the -Z or +Z thrusters in each thruster cluster continuously for a specified duration. The accuracy with which a given maneuver can be executed is a function of the propulsion system behavior and the attitude control system that maintains the pointing of the spacecraft during thruster firings. Maneuver execution errors are described in terms of components that are proportional to the commanded ΔV magnitude and components that are independent of ΔV magnitude. The maneuver execution accuracy requirements are listed in Table 4, with TCM-1 having a higher proportional component, because TCM-1 is the first TCM implemented prior to calibration of the thrusters.[7]

Table 4. Maneuver Execution Errors

Maneuver Error	TCMs 1-2	TCMs 3-6
Proportional magnitude error (3σ)	8%	5%
Proportional pointing error, per axis (3σ)	50 mrad	50 mrad
Fixed magnitude error (3σ)	4 mm/s	4 mm/s
Fixed pointing error, per axis (3 σ)	4 mm/s	4 mm/s

Approach Delivery and Knowledge Accuracy

The combination of Orbit Determination (OD) errors and maneuver execution errors mapped to the atmospheric entry interface point is referred to as TCM delivery accuracy. Atmospheric entry state knowledge accuracy (position or velocity) is the OD knowledge accuracy (measured by the position or velocity covariance norm) at entry based on an OD data cutoff (DCO) at Entry - 6 hours. This time is driven by the DCO of the last opportunity to update the EDL Parameter Update (EPU-4) file needed to initialize the guidance system. Each TCM has an associated entry delivery uncertainty, which is made up of errors in orbit determination and maneuver execution. In order to satisfy the physical constraints of the EDL system and to limit the size of the landing error ellipse, the navigation system is required to achieve the specified inertial EFPA with an uncertainty of ± 0.20 deg (3σ). The out of plane component of the delivery is constrained by a cross track error not larger than 5 km (3σ).

Filter Configuration and Assumptions

A summary of the baseline and no margin OD filter assumptions and error sources for the orbit determination results is shown in Table 5 (note that changes with respect to the baseline are highlighted in orange). ACS events (i.e. spacecraft attitude maneuvers and thruster firings for spin-rate control) are included throughout the interplanetary trajectory at the frequency specified in the Table. The ΔV from each ACS event in the data arc was estimated; the ΔV from each ACS event beyond the data cutoff was considered. The solar radiation pressure is estimated as a bias parameter only because the high-fidelity solar radiation model requires no stochastic parameters. However, to account for the RTG thermal radiation

Table 5. No-Margin and Baseline Orbit Determination Error Assumptions

Error Source	Estimate or Consider	A Priori Uncertainty (1σ)		Correlation Time	Update Time
		Baseline	No-Margin		
Epoch State Position	Est.	1000 km	1000 km	-	-
Epoch State Velocity	Est.	1 km/s	1 km/s	-	-
X-Band 2-way Doppler	-	0.1 nm/s	0.05 mm/s	-	-
Range	-	3 m	3 m	-	-
ΔDOR	-	60 ps	40 ps	-	-
Range Bias	Est	2 m	1 m	0	Per pass
Station Locations	Con.	Full 2003 Covariance	Full 2003 Covariance	-	-
Quasar Locations	Con.	1 nrad	0.5 nrad	-	-
Pole X, Y	Est.	2 cm	0.2 cm	48 hr	6 hr
UT1	Est.	5 cm	0.5 cm	48 hr	6 hr
Ionosphere day/night	Est.	38/38 cm	38 / 22 cm	6 hr	1 hr
Troposphere wet/dry	Est.	1.0 / 0.16 cm	0.8 / 0.16 cm	6 hr	1 hr
Mars and Earth Ephemerides	Con.	DE438 Cov.	0.5 x DE438 Cov.	-	-
Earth GM	Con.	1.4×10^{-3} km^3/s^2	1.4×10^{-3} km^3/s^2	-	-
Moon GM	Con.	1.5×10^{-4} km^3/s^2	1.0×10^{-4} km^3/s^2	-	-
Mars GM	Con.	2.8×10^{-4} km^3/s^2	1.82×10^{-4} km^3/s^2	-	-
Solar Pressure SRP Fourier Coefficients	Est.	$5.2 \times 10^{-7} – 10.4 \times 10^{-7}$ km^2	$2.6 \times 10^{-7} – 5.2 \times 10^{-7}$ km^2	-	-
RTG Thermal Emission	Est.	3.0×10^{-12} km/s^2	3.0×10^{-12} km/s^2	30 days	7 day
ACS Event ΔV Per Axis	Every 7 days from L + 15d until E -8d				
	Est.	2.5 mm/s (before E - 45d) 1.5 mm/s (after E - 45d)	0.2 mm/s (before E - 45d) 0.1 mm/s (after E - 45d)		
Maneuver Execution Errors		Range of values for current set of cases			
TCM-4 (E-8.6 days)	Est.	2.37 - 3.02 mm/s	2.07 – 2.80 mm/s	-	-
TCM-5 (E-2.6 days)	Est.	1.90 - 1.91 mm/s	1.51 - 1.52 mm/s	-	-

a stochastic acceleration is estimated. For the analyses described in this paper, the relative Earth-Mars position errors of the DE423 covariance (applied to the DE430 ephemeris) were used. For M2020, an Earth-Mars ephemeris update will be provided 6 months prior to landing. Predicted 1-sigma uncertainties up to ten years after the data cut-off are up to 115 meters in the line-of-sight direction, 190 meters in right ascension, and 260 meters in declination[7].

The TCM-5 EFPA and cross track delivery accuracy results are shown in Figure 6. Entry knowledge results (position and velocity) are shown in Figure 7. For these figures, results are shown as a function of launch day and landing site. Figure 6 shows that the baseline TCM-5 delivery EFPA accuracy easily meets the 0.20 deg (3σ) requirement for all launch days. Figure 7 shows that for all launch days, the E − 6 hr entry knowledge accuracies (position and velocity) are well below the requirements of 2.8 km and 2.0 m/sec, respectively[7].

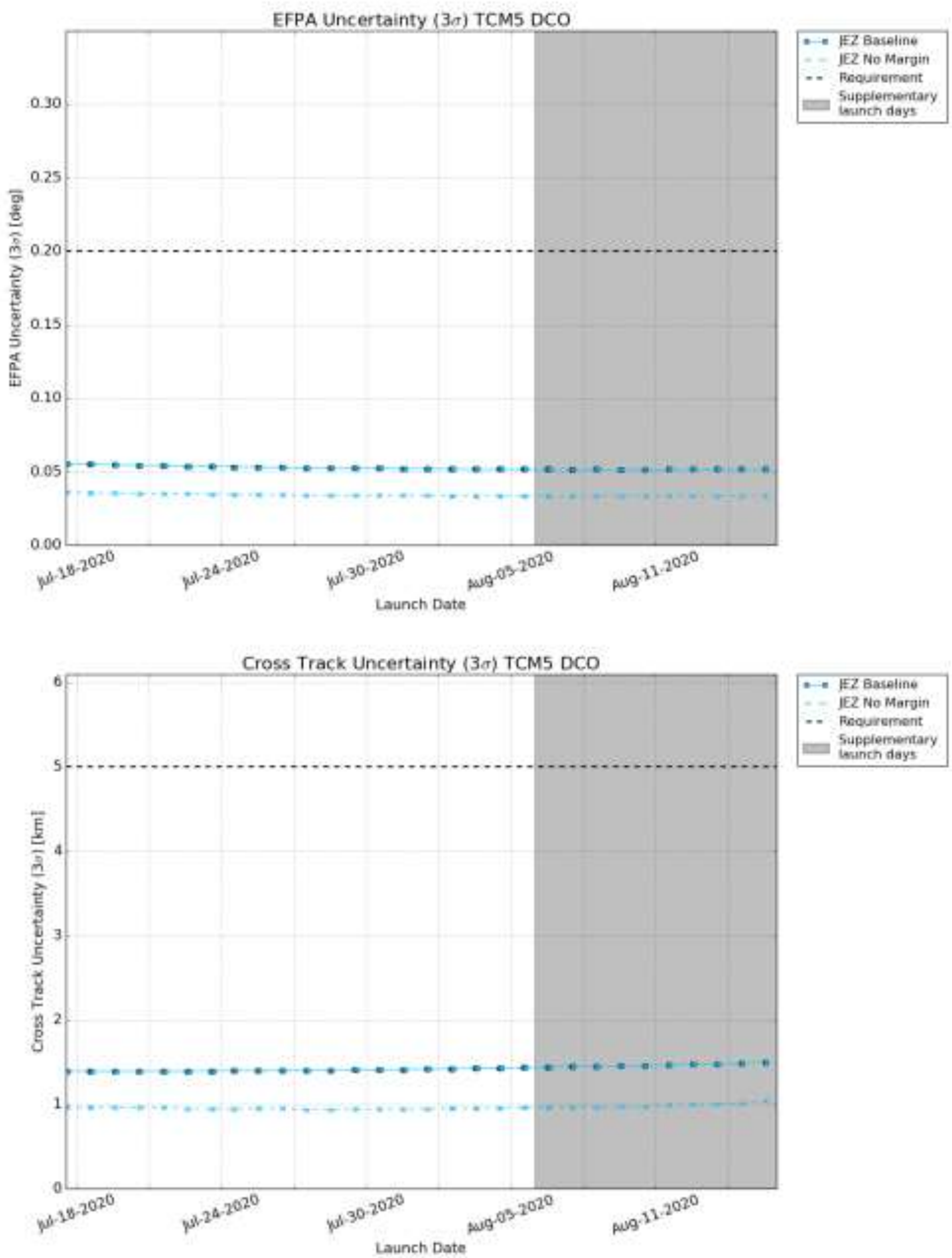

Figure 6. TCM-5 EFPA and Cross-Track Delivery Accuracy

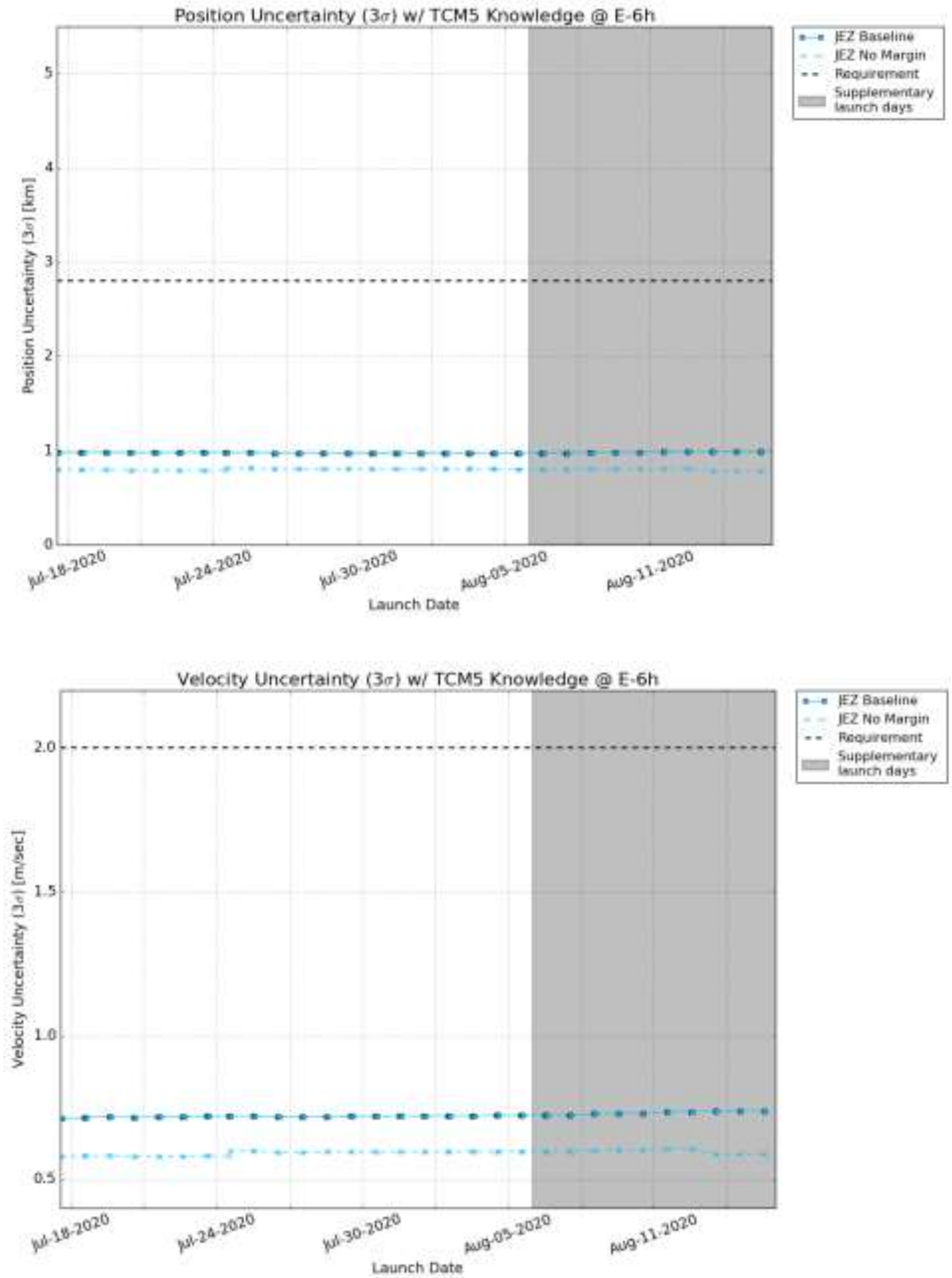

Figure 7. Entry – 6 Hour Position and Velocity Knowledge Accuracy

The No-Margin assumptions remove margin or conservatism in the error assumptions to produce values closer to the expected performance. The difference between the No Margin and Baseline cases quantifies the amount of margin included in the navigation design.

Approach Delivery Accuracy Sensitivities

A series of parameterized sensitivity studies for the approach phase was performed in order to determine the effects of changes to data assumptions and modeling uncertainties on the TCM-4 and TCM-5 delivery accuracies and the entry knowledge accuracies. For all cases studied, only a single parameter or model is changed at a time with respect to the baseline. The changes in the error sources are summarized in Table 6. In general, the Improved case uses half the Baseline uncertainty value for a given parameter, whereas the Degraded case uses twice the Baseline value. Other permutations evaluated include different tracking data combinations with the Baseline assumptions[7].

Table 6. Parameter Variation Error Assumptions for Sensitivity Analysis

Error Source	Estimate or Consider	Uncertainties (1σ)			
		Improved	No Margin	Baseline	Degraded
2-way Doppler weight (mm/s)	-	0.05	0.05	0.1	0.2
Range weight (m)	-	1.5	3	3	6
ΔDOR weight (ps)	-	30	40	60	120
ΔDOR latency (hr)	-	12	8	24	48
ACS Turns (per axis, mm/s)	Est.	0.5 x Baseline	0.2 or 0.1	2.5 or 1.5	2 x Baseline
TCM-4 (per axis, mm/s)	Est	0.5 x Baseline	5% Prop + 2 mm/s Fixed	5% Prop + 4 mm/s Fixed	2 x Baseline
TCM-5 (per axis, mm/s)	Est	0.5 x Baseline	5% Prop + 2 mm/s Fixed	5% Prop + 4 mm/s Fixed	2 x Baseline
SRP Fourier Coefficients (m^2)	Est	0.5 x Baseline	0.5 x Baseline	0.52 to 1.04	2 x Baseline
RTG Thermal Emission ($x10^{-12}$ km/s^2)	Est. (Stoch)	0.5 x Baseline	3	3	2 x Baseline
Range Bias (m)	Est. (Stoch)	1	1	2	4
Day Ionosphere (S-band, cm)	Est. (Stoch)	0.5 x Baseline	38	38	2 x Baseline
Night Ionosphere (S-band, cm)	Est. (Stoch)	0.5 x Baseline	22	38	2 x Baseline
Wet Troposphere (cm)	Est. (Stoch)	0.5 x Baseline	0.8	1.0	2 x Baseline
Dry Troposphere (cm)	Est. (Stoch)	0.5 x Baseline	0.16	0.16	2 x Baseline
X/Y Pole (cm)	Est. (Stoch)	0.5 x Baseline	0.2	2.0	2 x Baseline
UT1 (cm)	Est. (Stoch)	0.5 x Baseline	0.5	5.0	2 x Baseline
Quasar Locations (nrad)	Con	0.5	1	1	2
Earth-Mars Ephemeris scale	Con	0.5 x Cov	0.5 x Cov.	1.0 x Cov	2.0 x Cov.
Mars GM (km^3/s^2)	Con	-	1.82	2.8	-

Figures 8 through 10 show bar charts of the sensitivity analysis results. Each chart lists the individual cases along the bottom, beginning with the Baseline (green) and No-Margin (yellow) cases, followed by the variations of error assumptions and data weights (blue for Improved, red for Degraded), followed by tracking data combinations (orange).

For comparison, a red dashed horizontal line indicates the requirement level, and a green dotted horizontal line indicates the Baseline level. Bars that extend past twice the requirement level have their value listed in the top of the bar. Figure 8 shows the EFPA sensitivities at the TCM-4 and TCM-5 DCOs. Inspection of the plots reveals that the EFPA and delivery uncertainty is most sensitive to TCM execution error and ACS events. The cross-track delivery, as shown in Figure 9, is most sensitive to TCM execution error and ACS events as well but also to ΔDOR parameters (weight, latency, and quasar position). The data type variations show that the solution is most sensitive to loss of range and ΔDOR measurements. Figure 10 shows entry state knowledge sensitivities at the E – 6-hour DCO. Both the position and velocity entry knowledge are most sensitive to quasar positions.

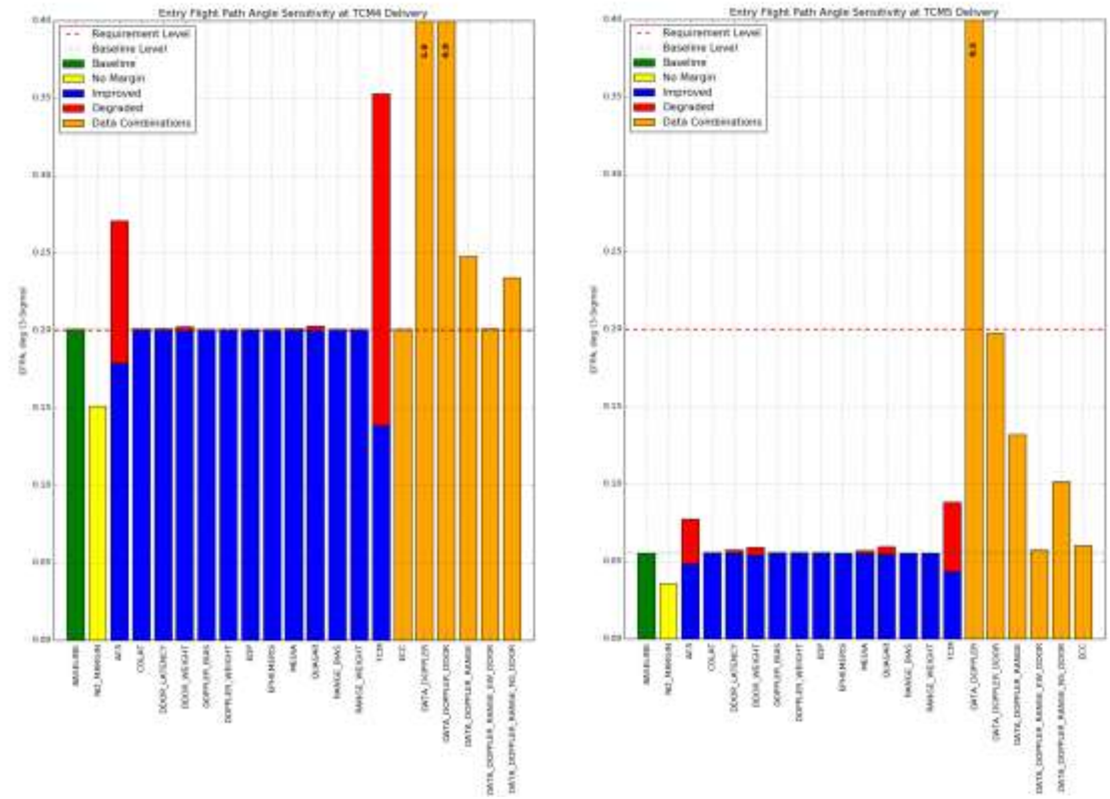

Figure 8. TCM-4 and TCM-5 EFPA Delivery Sensitivities

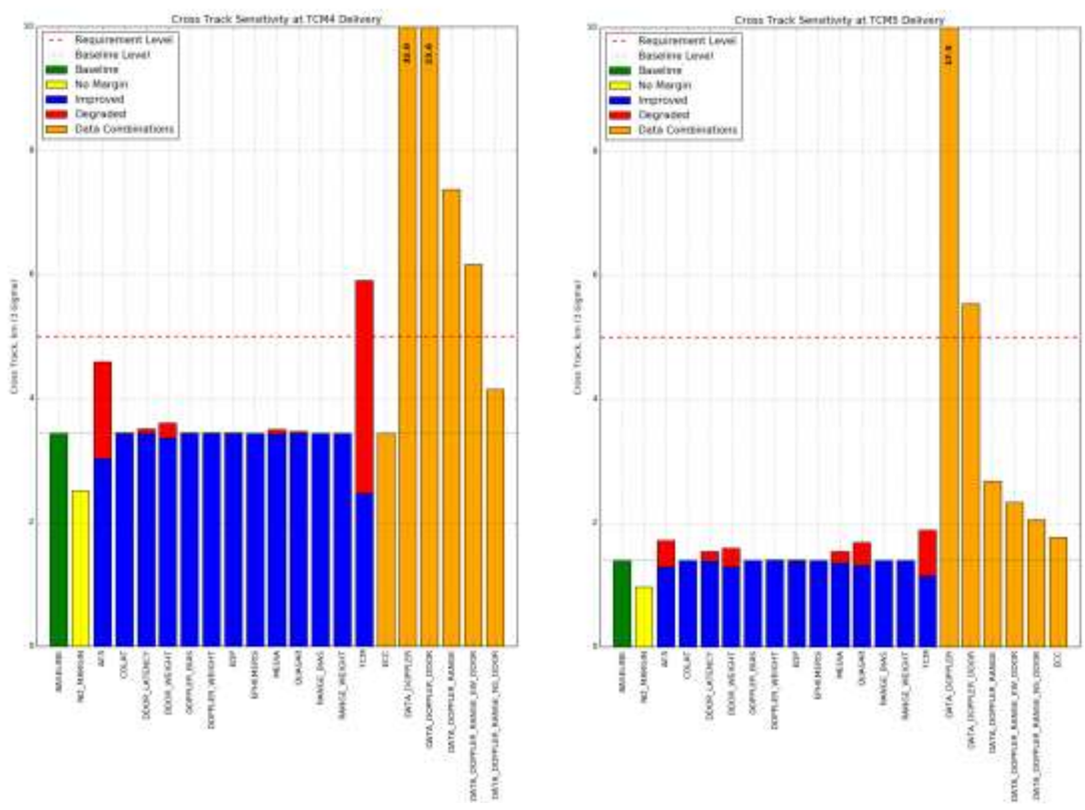

Figure 9. TCM-4 and TCM-5 Cross-Track Delivery Sensitivities

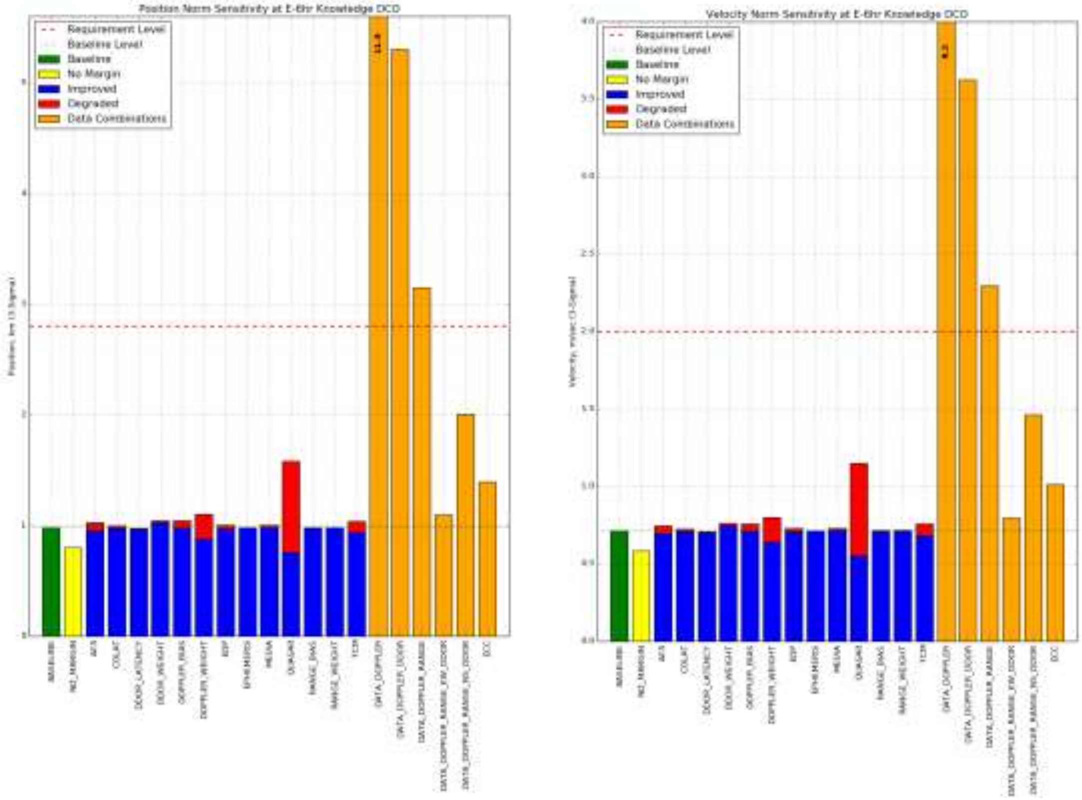

Figure 10. Position and Velocity Knowledge Sensitivities at Entry – 6 Hours

Propulsive Maneuver Analysis

The goal of the maneuver strategy and design is to use TCMs to adjust or fine-tune the trajectory such that navigation requirements are met under various constraints. Sufficient propellant must be provided to account for uncertainties such as launch vehicle injection dispersions and requirements such as those dealing with planetary protection. The TCM propellant allocation is 45.0 kg and includes usages associated not only with all TCM burns but also with turns required for implementing TCM-1 (the rest of the TCMs will be executed in no-turn vector mode). In general, a TCM contains both deterministic and statistical components. The deterministic component is used to reshape the trajectory after injection such that it will achieve the desired final aimpoint at Mars. For example, TCM-1 and TCM-2 usually have a deterministic component for correcting the injection bias required for planetary protection. Other TCMs are inherently statistical in nature (i.e., non-deterministic) in that they are designed to correct for statistical errors from injection, orbit determination and prediction, and maneuver execution. The statistical maneuver analysis process estimates the ΔV budget and corresponding propellant usage required for a given probability level (e.g., 99%)[7].

Mission ΔV and Propellant Statistics

As described earlier, TCM-1, TCM-2, and TCM-3 have a deterministic component in the reference trajectory. Together, these TCMs implement the ΔV required to correct for injection aimpoint biasing, and to achieve the desired entry target. In general, each of the TCMs will also have a statistical component that is required for correcting navigation errors. TCM ΔV and propellant statistics are estimated by performing 5000-sample Monte Carlo analyses. These analyses include dispersions from the injection covariance matrix (ICM), TCM execution errors, and orbit determination uncertainties. To estimate TCM propellant usage, first the ideal (or desired) ΔV statistics are computed. The ideal ΔV represents the design inertial velocity change in the trajectory and does not reflect losses due to propulsion system inefficiencies, such as thruster cant angle losses and finite burn losses, or particular maneuver implementation modes. Figure 11 shows the total deterministic ΔV (TCM-1 + TCM-2 + TCM-3) and the 99% Ideal ΔV for each daily launch window. The total deterministic ΔV shows the cost for removing the injection bias while the

99% Ideal ΔV illustrates the additional costs required for removing other statistical uncertainties (ICM, OD, and maneuver execution errors). Total deterministic costs are approximately between 2.0 and 2.5 m/s for all launch dates and the 99% Ideal ΔVs are roughly 4 to 6 m/s higher[7].

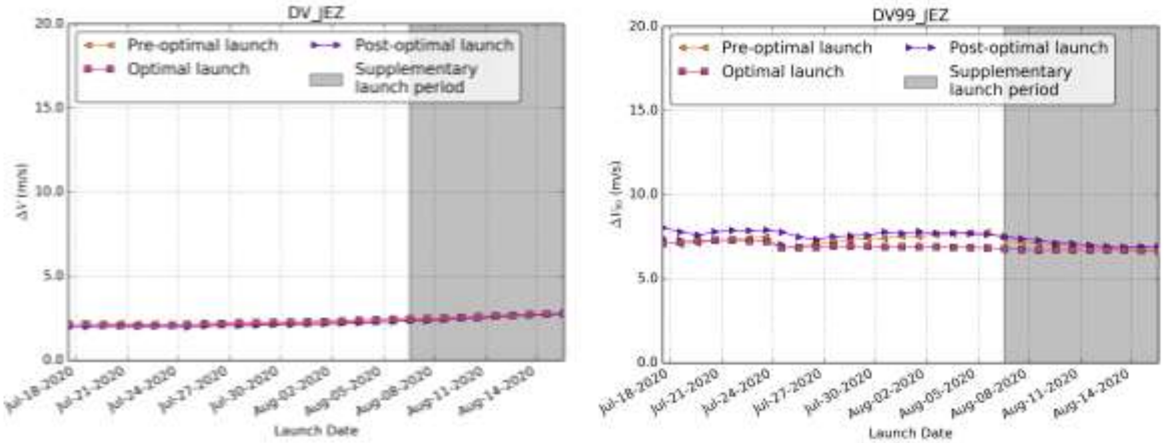

Figure 11. Total Deterministic (TCM-1 + TCM-2 + TCM-3) ΔV and 99% Ideal ΔV

The Ideal ΔV statistics are then converted to implemented ΔV. The implemented ΔV accounts for thruster cant angle losses (55.6% for axial thrusters and 30.5% for lateral thrusters), lateral ΔV losses due to finite burn arcs (4.7%), vector mode costs, and other maneuver implementation costs dictated by the Sun and Earth pointing constraints for TCM-1. The implemented ΔV is subsequently used to calculate the propellant mass estimate using effective Isp for each sample of the Monte Carlo analysis. Statistical propellant cost analyses have been performed for all cases and are summarized in Figure 12 which shows the 99% propellant usage. Overall, the 99% propellant usages for all cases are comfortably below the maximum propellant allocation of 45 kg.

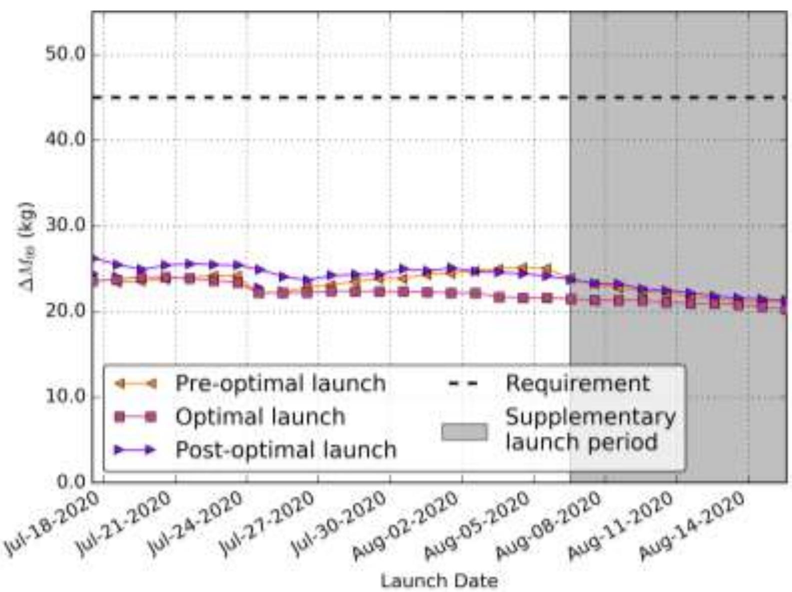

Figure 12. 99% Propellant Usage

A detailed ΔV and propellant usage breakdown for the highest propellant case corresponding to day 1 at the close of the launch window is given in Table 7 which includes: deterministic ΔV of the reference trajectory, Ideal ΔV statistical distributions, statistics for the Implemented ΔV, and statistics for the propellant usage (burn mass). As stated earlier, TCM-1, TCM-2, and TCM-3 have a deterministic component in the reference trajectory but in this case, the size of TCM-3 is less than 10^{-4} so it is not reflected in the table. This is expected since TCM-3 is months after launch and therefore is not in an advantageous location to correct for injection bias[7].

Table 7. Deterministic, Ideal, Implemented ΔV, and Propellant Statistics for Worst Case (07/17)

Burn	Determ. ΔV (m/s)	Ideal ΔV (m/s)			Implemented ΔV (m/s)			Propellant Mass (kg)		
		μ	σ	ΔV99	μ	σ	ΔV99	μ	σ	ΔM99
TCM-1	1.10	2.47	1.34	6.61	3.79	2.16	10.28	7.30	4.26	20.12
TCM-2	0.85	0.76	0.07	0.99	1.75	0.16	2.24	3.35	0.31	4.28
TCM-3	0.00	0.39	0.04	0.48	0.67	0.08	0.87	1.27	0.15	1.64
TCM-4	0.00	0.09	0.04	0.20	0.18	0.08	0.41	0.33	0.15	0.78
TCM-5	0.00	0.02	0.01	0.03	0.03	0.01	0.07	0.05	0.03	0.13
Total	**1.96**	3.72	1.35	**8.03**	6.41	2.17	**13.15**	12.30	4.28	**25.55**

50-Year Planetary Protection

The launch targets are biased away from Mars in order to satisfy NASA's 50-year Planetary Protection (PP) requirement for impact probability of the upper stage at Mars.[6] The 99th percentile probability of impact for the open, close and intermediate launch points of the launch window for every day in the launch period are shown in Figure 13. Due to the usage of launch polynomials, the "floor" in these estimates, typically driven by the number of samples drawn during the Monte Carlo Analyses, is very close to the highest probability of impact value[8]. The worst-case probability of impact is 0.67×10^{-4} and occurs on launch day 10 (07/26/20) at the optimal launch time.

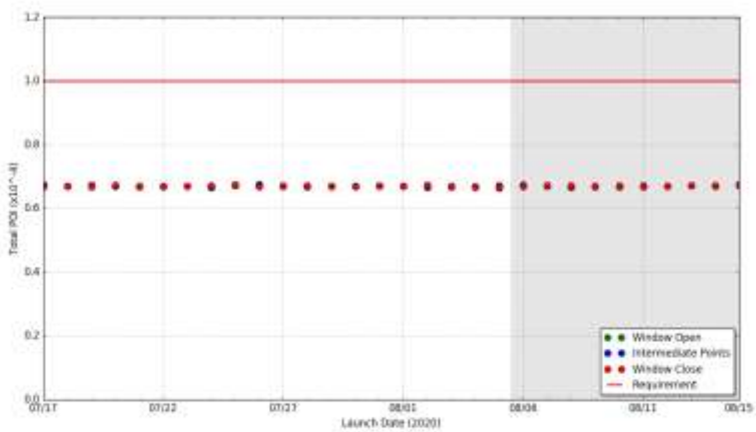

Figure 13. Total Probability of Impact

Non-Nominal Impact Probability

In addition to injection aimpoint biasing that ensures the probability of Mars impact by the launch vehicle upper stage does not exceed 1.0×10^{-4} over a 50-year period from launch, PP requirements also state that the overall probability of non-nominal impact of Mars due to failure during the Cruise and Approach phases shall not exceed 1.0×10^{-2}. A non-nominal impact is defined as an impact that could result in the break-up of the spacecraft and release of terrestrial contaminants on Mars. The probability of non-nominal impact for TCMs 1 through 4 is defined as the probability of impact after each TCM, P(i), multiplied by the probability that the following maneuver does not occur, Q(i+1). Preliminary calculations have shown that if all TCMs are targeted directly to the nominal entry conditions at Mars, the overall non-nominal impact probability exceeds the requirement of 1.0×10^{-2} with TCMs 1, 2, and 3 being the major contributors. Consequently, a strategy of biasing the aimpoints for TCMs 1 and 2 has been adopted in order to reduce their contributions to the non-nominal impact probability. In this strategy the aimpoints for TCMs 1 and 2 are determined by a chained TCM-1, -2, and -3 re-optimization design that minimizes the combined total ΔV cost. The non-nominal impact probability results are shown in Figure 14.[7]

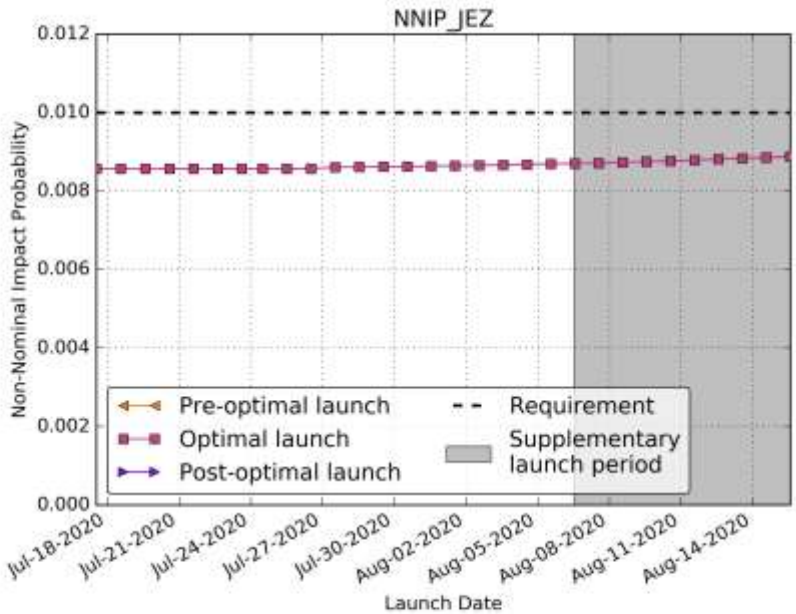

Figure 14. Probability of Non-Nominal Impact

CONCLUSIONS

This paper has summarized the M2020 launch/arrival strategy, the Navigation and Maneuver Design, and presented results to demonstrate that the Mission Design and Navigation requirements for the M2020 mission are satisfied. This strategy consists of a 20-day launch period (and up to 10 contingency launch days) that provide EDL communications via UHF to MRO and MAVEN and partial X-band Direct-To-Earth tones. Six trajectory correction maneuvers (TCMs) are planned in order to achieve the required entry delivery and knowledge accuracies.

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