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MARS RECONNAISSANCE ORBITER NAVIGATION STRATEGY FOR SUPPORT OF MARS 2020 MISSION'S ENTRY, DESCENT AND LANDING SEQUENCE

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The Mars Reconnaissance Orbiter provided primary relay support during the Mars 2020 mission's entry, descent, and landing sequence on February 18, 2021. To position the orbiter for relay support during this sequence, two propulsive maneuvers were performed: the first on September 2, 2020 and the second on January 20, 2021. This paper documents the maneuver strategy developed by the navigation team for positioning the Mars Reconnaissance Orbiter to within phasing requirements to support the Mars 2020 mission during landing and provides details on how well those phasing requirements were met.

INTRODUCTION

The Mars Reconnaissance Orbiter (MRO), in its fifth extended mission orbiting Mars, provided telecommunication relay support for NASA's Mars 2020 mission (M2020) during the Entry, Descent and Landing (EDL) sequence on February 18, 2021. In the past, MRO supplied relay support during the EDL sequences of other spacecraft such as the Mars Phoenix Lander in May 2008,[1] the Mars Science Laboratory (MSL) in August 2012,[2] ESA's ExoMars EDL Demonstrator Module (EDM) in October 2016,[3] and more recently InSight in November 2018.[4] MRO's support of M2020 EDL occurred soon after the end of the high atmospheric density season. This paper will discuss the MRO navigation strategy, as well as the operational challenges, to support M2020 in achieving the EDL phasing requirements.

For telecommunication and possible imaging support during the M2020 EDL event, M2020 requested that MRO transition to a 3:30 PM Local Mean Solar Time (LMST) at the orbit ascending

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node at the time of M2020 EDL; 3:00 PM is the Primary Science Orbit (PSO) LMST. M2020 also requested post-landing relay support from MRO for surface operations. The requirements for MRO's support of M2020 EDL were as follows:

- The MRO orbit LMST at M2020 EDL must be between 3:15:00 PM and 3:35:00 PM.
- MRO must phase within ± 30 seconds of the specified M2020 entry epoch (within ± 1.6 degrees of a requested latitude target specified at M2020 entry).

MRO nominally implements a propulsive maneuver in one of two standard maneuver attitudes: in-plane (along spacecraft velocity vector) or out-of-plane (along spacecraft angular momentum vector). Typical PSO maintenance maneuvers (Orbit Trim Maneuvers or OTMs) are executed in-plane for apses height control; most have been performed at orbit periapsis to raise orbit apoapsis. These maneuvers are used to maintain the PSO ground track walk repeat error between ± 60 km. Orbit LMST control (inclination change) is achieved via out-of-plane maneuvers, referred to as Orbit Change Maneuvers (OCMs). Orbit phasing is accomplished through in-plane maneuvers, referred to as Orbit Synchronization Maneuvers (OSMs). An OSM produces a change in the orbit period that, over a given duration, achieves a desired total MRO orbit down-track timing change.

OCM-4A was performed in October 2019 to target the LMST required (3:30 PM) for M2020. With average Mars atmospheric drag ΔVs (change in orbital velocity needed to counter the atmospheric drag effect) peaking a few months prior to the time of M2020 EDL, the orbit phasing effort of MRO with the M2020 EDL sequence was not expected to be trivial. Out of four planned OSMs, the first (OSM-1) and third (OSM-3) were performed in September 2020 and January 2021 prior to M2020 landing to place MRO at the requested EDL target time. The other two planned maneuvers were deemed unnecessary (OSM-2 and OSM-4) as well as the contingency maneuver planned for only one week prior to M2020 EDL (OSM-4C) due to the phasing requirement of ± 30 seconds being already met by OSM-3. This paper will discuss the challenges faced in the designs of these maneuvers which required a close tracking of the predicted timing offset from the M2020 relay target given the expected larger down-track timing uncertainties. The evolution of the MRO phasing offset from the final relay target time requested by M2020 will also be presented as well as the final offset based on the reconstructed MRO trajectory at the time of EDL.

Unlike earlier EDL supports, MRO was expected to provide M2020 EDL support using a "bent-pipe" relay capability. This involved MRO acquiring data from M2020 and transmitting in near-realtime the data to Earth while the spacecraft tracked and slewed. Delivering very accurately MRO to the desired atmospheric entry point for M2020 EDL was critical for the special "track and slew" sequence in which the HGA tracks the Earth while a slew maneuver is in progress. This was the first ever flight demonstration of the bent-pipe telecommunications capability with HiRISE imaging for MRO.[5]

MRO MISSION OVERVIEW

MRO has completed several missions at Mars: the Primary Science Phase, the Extended Science Phase, and four extended missions (EM1, EM2, EM3 and EM4). MRO is currently in its fifth extended mission (EM5). As an asset of the Mars Exploration Program, MRO has performed science observations and provided telecommunication relay support to the Mars Exploration Rover since January 2004 and the Mars Science Laboratory since August 2012.[2] It also supplied relay support to the Mars Phoenix lander in May 2008,[1] observed the close flyby of Comet Siding Spring at Mars in October 2014,[6] imaged the ExoMars lander Schiaparelli in October 2016[3] and provided EDL relay support to the InSight lander mission. In addition to supporting M2020 EDL, MRO plans to provide telecommunication support of ESA's ExoMars 2022 mission in June 2023.[7]

MRO Spacecraft

The spacecraft axes, as shown in Figure 1, are defined such that the X-axis is directed along the velocity vector, the Z-axis is along the nadir direction, and the Y-axis completes the triad. The six engines for Mars Orbit Insertion (MOI) and the six Trajectory Correction Maneuver (TCM) thrusters are located along the +Y direction. The large solar panels are along the X-axis, canted 15 deg towards the +Z direction. The 3-meter diameter High Gain Antenna (HGA) is located opposite the nadir deck where the majority of the science instruments are placed. During science operations the nadir deck is configured towards Mars. Both solar panels and HGA swivel to track the Sun and Earth, respectively. MRO is gravity gradient-stabilized to sustain the nadir-to-planet orientation. Spacecraft attitude is maintained by the Reaction Wheel Assembly (RWA); this consists of three 100 Nms wheels mounted perpendicular to each other, augmented by a fourth redundant wheel in a skewed orientation. The monopropellant propulsion subsystem uses three sets of thrusters: the aforementioned MOI and TCM thrusters, and the Attitude Control System (ACS) thrusters. The TCM thrusters have been used for maneuvers since February 2007. The ACS system uses balanced thrusters where the thruster pairs are fired together and arranged such that a net zero ΔV is imparted. The spacecraft bus built by Lockheed Martin provides a stable platform for the payload science instruments. These instruments, mounted for observation on the +Z axis of the spacecraft (nadir deck), are used to perform remote sensing of the Martian atmosphere, surface, and subsurface. They include the High Resolution Imaging Science Experiment (HiRISE) camera, the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM), the Mars Climate Sounder (MCS), the Mars Color Imager (MARCI), the Context Camera (CTX), the Shallow Subsurface Radar (SHARAD), and the Electra ultra-high-frequency (UHF) engineering payload. High resolution imagery is performed using the HiRISE camera. This key resource is able to supply imaging of orbiting or landed assets on Mars as well as observe possible future landing site locations. Relay telecommunication support in the UHF frequency range is provided by the Electra instrument. Since March 19, 2018 MRO has been relying on its star tracker instead of the aging gyroscopes for attitude control during nominal operations. But gyros are still used during maneuver support and special operations such as EDL support.

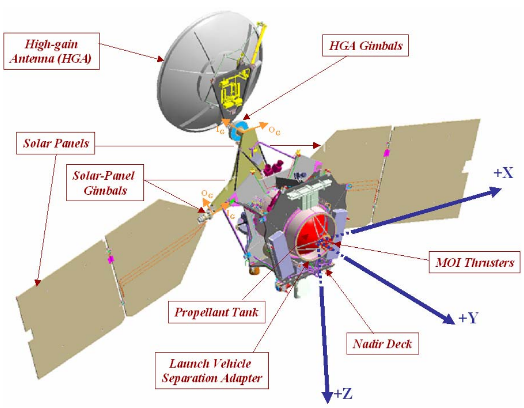


Figure 1: MRO Spacecraft

MRO Primary Science Orbit

The Primary Science Orbit (PSO) for MRO operations is a 252 km $\times$ 317 km altitude, sun-synchronous orbit with the periapsis frozen over the south pole and the ascending node at 3:00 PM $\pm$ 15 minutes. The osculating orbital elements are shown in Table 1 for the MRO orbit containing the M2020 EDL event. The orbit is designed to exactly repeat after 4602 revolutions in 349 sols (1 sol = 1.0275 days), with separation between ground tracks of less than 5 km at the equator.

The near-repeat cycle used for science planning is a 211-orbit cycle (16 sols) that walks about 0.5 deg (32.5 km) in longitude westward from the previous cycle. The orbit maintenance is done based on this near-repeat cycle via propulsive maneuvers (OTMs). Note that orbit maintenance was postponed until after M2020 EDL and the orbit remained outside the ascending node PSO 3:00 PM $\pm$ 15 minutes requirement in support of M2020 EDL at 3:30 PM.

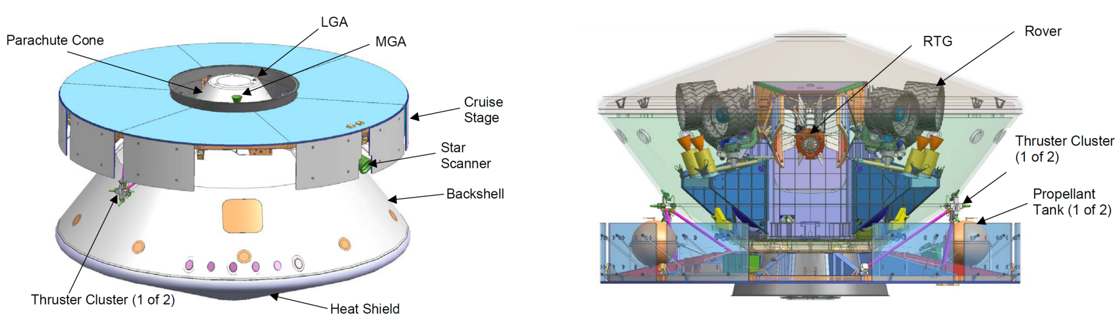
Table 1: Osculating Orbital Elements on February 18, 2021 (MRO Orbit 68281)

Periapsis Epoch: 18-Feb-2021 20:13:06.142 ET		**Additional Orbit Information**	
Semi-Major Axis (a)	3645.3006 km	Period (T)	111.3686 min
Eccentricity (e)	0.0052	Periapsis Altitude (H_p)	250.1828 km
Inclination (i)	93.1635°	Apoapsis Altitude (H_a)	312.0069 km
Argument of Periapsis (ω)	269.4897°	Ascending Equator Crossing Epoch (Near M2020 EDL): 18-Feb-2021 20:40:58.379 ET	
Right Ascension of Node (Ω)	271.5079°		
True Anomaly (v)	0.0°	Apoapsis Epoch: 18-Feb-2021 21:08:56.053 ET	

MARS 2020 MISSION OVERVIEW

M2020 launched from Cape Canaveral Air Force Station on July 30, 2020. Following a nearly seven month cruise, M2020 arrived at Mars on February 18, 2021 and delivered the Perseverance rover to Jezero Crater, beginning a planned surface mission for at least one Mars year. As part of NASA's Mars Exploration Program, Perseverance will seek signs of ancient Martian life, conduct experiments and test technologies beneficial to future human Mars exploration, and collect rock and soil samples for return to Earth by a potential sample return mission. The M2020 landing site was 18.4° N, 77.5° E in the Jezero Crater, now known as the Octavia E. Butler landing site.[8]

Figure 2a shows the M2020 spacecraft in cruise configuration. An adaptation of the MSL spacecraft design, M2020 was a spin-stabilized spacecraft with a nominal spin rate of 2 rpm. The M2020 flight system consisted of the following components: cruise stage, aeroshell (heatshield and backshell), descent stage, and the Perseverance rover. Figure 2b shows a view of the M2020 spacecraft in the launch configuration and includes the location and orientation of the Perseverance rover, RTG, thruster clusters, and propellant tanks.[9]



(a) Mars 2020 Cruise Configuration

(b) Mars 2020 Launch Configuration

Figure 2: Mars 2020 Cruise and Launch Configurations

The cruise stage included solar panels, the propulsion system which is composed of two propellant tanks and two thruster clusters, the Attitude Control System, which included a star scanner, IMU, and Sun sensors, and antennas (one low gain and one medium gain) for X band communications with Earth. Both antennas were oriented in the spacecraft $-Z$ direction. The cruise stage was separated from the entry vehicle assembly 10 min prior to atmospheric entry.[9]

M2020 relied primarily on MRO for relaying the telemetry to Earth during EDL, with additional support provided by Mars Atmosphere and Volatile Evolution (MAVEN) mission. In this paper, only the role that MRO played in relaying the M2020 data during EDL is discussed. See Reference 10 for details about how MAVEN supported M2020 EDL.

SELECTION PROCESS FOR MARS 2020 EDL TARGET

MRO had been identified as the prime NASA relay service provider for the M2020 lander. It was expected to provide support for up to 12 sols after EDL, which would aid the UHF and data flow performance analysis. This level of support included enabling successful forward- and return-link data transfers to M2020. The MRO project had agreed to maintain MRO's orbit for the relay support for at least the first seven sols (prime support period) of the M2020 surface mission and continue to support surface operations thereafter. Per MRO-M2020 Navigation OIA-010 (Operational Interface Agreement), the final tolerances allowable in achieving the prescribed targets were the following:

- Time of target areocentric latitude crossing ($\pm$ 30 seconds), equivalent to 1.6 degrees in areocentric latitude
- The targeted LMST is 3:30 PM
- The achieved LMST should be not earlier than 15 minutes before the LMST target and not later than 5 minutes after the LMST target.

The EDL Relay Target Files (ERTFs) which M2020 supplied to the MRO Navigation Team on a regular basis contained the requested relay target.[11] ERTF-10 provided the requested phasing target that was used in the last phasing maneuver design. ERTF-15 was the final ERTF that gave the last prediction of the landing site just prior to M2020 EDL. See Appendix for the ERTF delivery history and the contents of ERTFs 10 and 15.

MARS 2020 EDL PHASING STRATEGY

Prior to the M2020 launch the MRO navigation team developed a maneuver plan for phasing MRO to the M2020 EDL target. The maneuver strategy was designed to mitigate timing uncertainties due to atmospheric drag and other orbital effects. A phasing approach with four planned maneuvers plus a contingency maneuver was implemented for correcting the timing offset from the desired EDL target. This strategy would minimize the chance of overshooting the phasing target. Prior to the first maneuver, the predicted phasing offset from the EDL target was about 75 minutes early, or approximately two-thirds of MRO's orbital period ($\sim$112 minutes). Orbit phasing is accomplished via in-plane OTMs, also referred to as Orbit Synchronization Maneuvers (OSMs). Ultimately, only two OSMs were needed. The first maneuver (OSM-1) was in the pro-velocity direction to increase MRO's orbit period. However the second maneuver (OSM-3) had to be done in the anti-velocity direction due to atmospheric variability and slight changes in the M2020 target. These two maneuvers would help reach the target within the $\pm$30 seconds phasing requirement.

Anticipated Atmospheric Drag and Navigation Timing Uncertainties

The atmospheric density variation is the largest contributor to errors in the MRO navigation accuracy, barring a significant maneuver execution error.[7] As shown in Figure 3, the atmospheric drag was anticipated to peak near 270 degrees L_s which was at about five months prior to M2020 landing (about 360 degrees L_s). The first maneuver was at this peak time while later maneuver placements would see lower density periods. In the past it was during very low density season that phasing was performed to support the EDL sequences of the Phoenix and MSL missions[1,2] and the risk mitigation efforts due to the Comet Siding Spring flyby of Mars.[6] However, this time the maneuver planning was done assuming a drag ΔV of 0.30 mm/s per orbit for the first phasing maneuver and later lowered to 0.25 mm/s and 0.20 mm/s per orbit for subsequent maneuvers (see the navigation timing uncertainties plots leading to EDL in Figure 4). Thus for OSM-3, lowering the drag ΔV assumption to 0.20 mm/s per orbit also allowed the data cutoff (DCO) for OSM-3 to be increased to 38 days prior to EDL (see Figure 4c) and still meet the $\pm$30 seconds requirement, returning to the nominal nine days for maneuver processing. Note that for all maneuvers except the final one, phasing was only to be corrected up to the navigation uncertainty level at a given maneuver opportunity to avoid potentially overshooting the target time. When planning the phasing strategy it was also recognized that the maneuver ΔV should not go below the minimum control capability of 20 mm/s for MRO maneuvers.

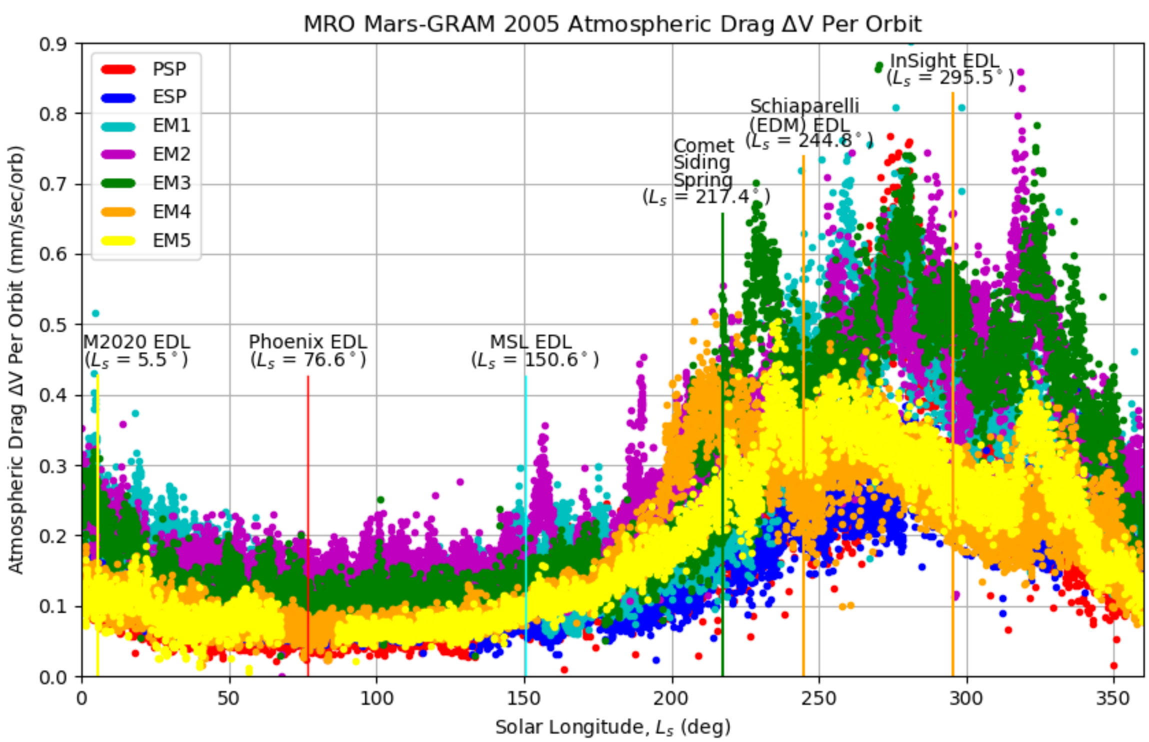
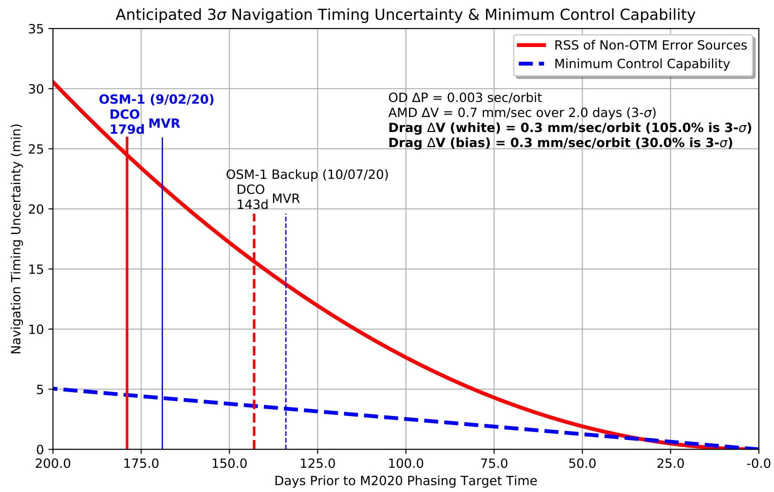
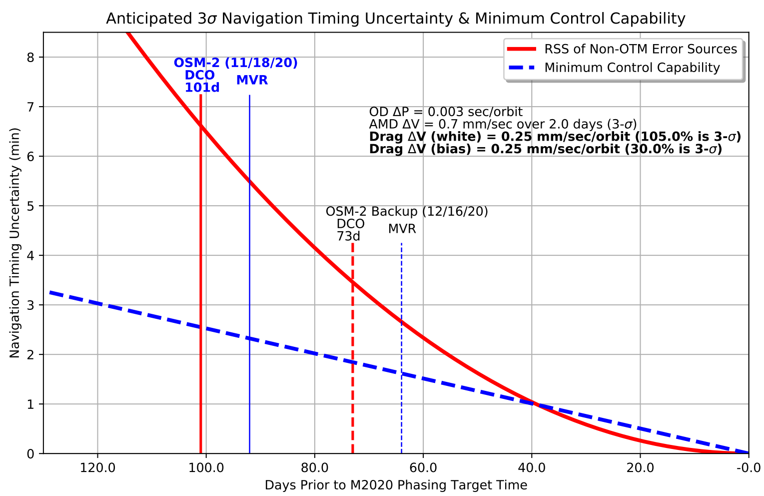


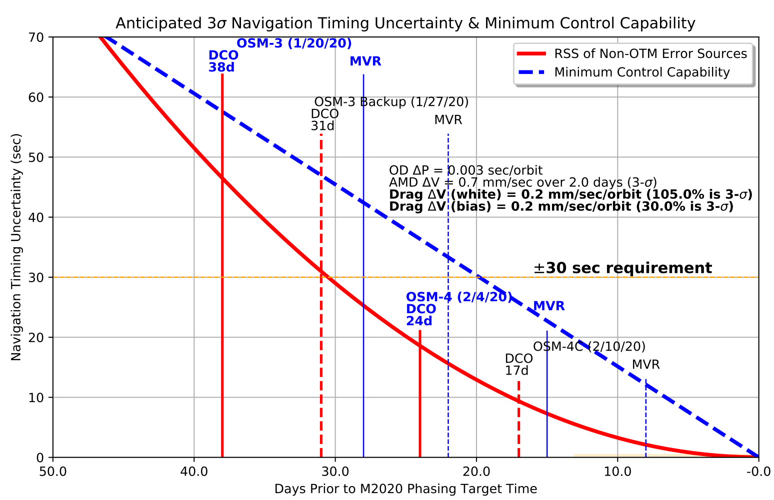
Figure 3: Atmospheric Drag ΔV Experienced by MRO through July 2021. *By mission phase: PSP = Primary Science Phase, ESP = Extended Science Phase, EM = Extended Mission (1-5)*



(a) OSM-1 (Drag ΔV = 0.30 mm/s/orbit)



(b) OSM-2 (Drag ΔV = 0.25 mm/s/orbit)



(c) OSMs 3, 4, and 4C (Drag ΔV = 0.20 mm/s/orbit)

Figure 4: Navigation Timing Uncertainties (3-σ) Prior to M2020 EDL Target Time

Solar Cycle

To reasonably predict the atmospheric density scale factor (DSF) when planning phasing maneuvers, consideration was given to the solar cycle as the Sun's activity has a significant effect on the volatility of Mars atmospheric behavior. Due to the solar activity being near a minimum, significant jumps in the DSF were not expected in spite of the high density period. The solar cycle 24 profile from the International Space Environment Service (ISES) is provided in Figure 5.

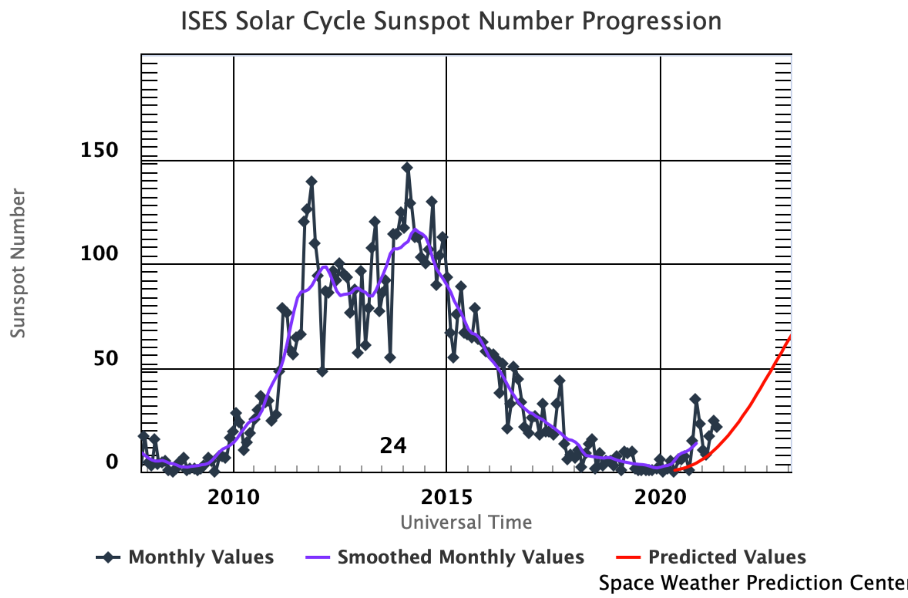
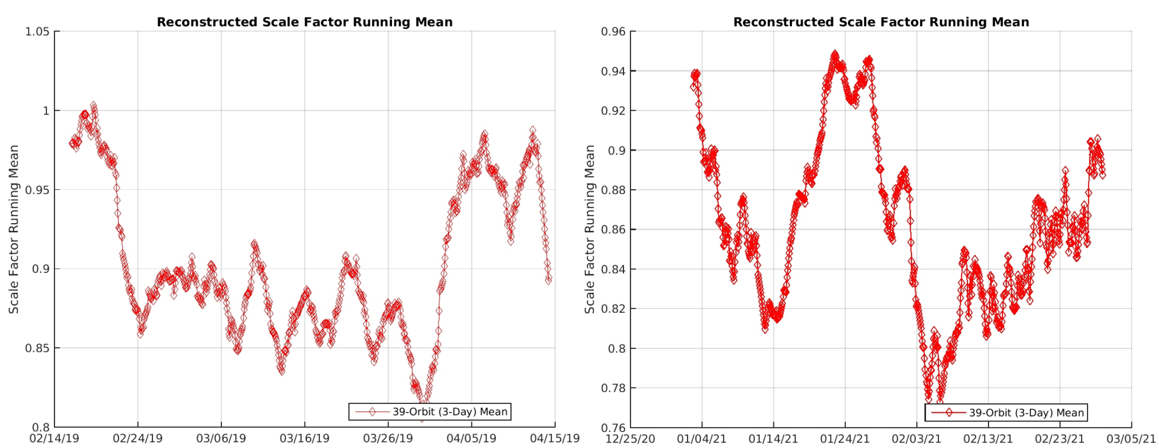


Figure 5: Solar Cycle Profile Through May 2021

Figure 6 shows the reconstructed DSF running mean for comparable seasons in Mars Years (MY) 34 and 35. The DSF history from the previous Mars Year 34 was used as a reference for the comparable season (similar solar longitude, L_s) in MY 35. Thus when planning OSM-1 and OSM-3 great attention was paid to the DSF trending for similar period a Mars year ago. From this engineering judgement 1.0 was chosen as the mean DSF when designing OSM-1 and 0.9 when planning OSM-3. This proved to be a prudent approach.



(a) February – April 2019 (MY 34 for Reference) (b) January – March 2021 (MY 35 for Operations)

Figure 6: Reconstructed Density Scale Factor Running Mean

Phasing Maneuvers

As previously mentioned, orbit phasing is accomplished via in-plane OSMs. OSM-1 (OTM-54), the first of two OSMs, was executed on September 2, 2020, about five and a half months prior to the M2020 landing. When the maneuver strategy was initially planned, the predicted phasing offset from the target time defined by ERTF-4 was about 75 minutes early. However, at the time of the final maneuver design (one week prior to OSM-1 execution) the phasing offset had reduced to about 65 minutes early. This may be attributed to the evolution of the orbit determination (OD) and the Mars dust activity – Dust Events A and B. Limiting the phasing correction to the navigation uncertainty ($\sim$24.6 minutes) at the OSM-1 DCO of about six months from the M2020 EDL target time (see Figure 4), OSM-1 was designed to remove about 44 minutes of phasing offset. This maneuver performed nominally, but with a slight overburn of 2.06%. Table 2 lists the estimated phasing errors at the M2020 EDL target prior to and following each phasing maneuver, as well as the expected down-track timing uncertainties at each maneuver opportunity. Targets given in ERTF-6 and ERTF-10 were used to design OSM-1 and OSM-3 respectively.

Table 2: Summary of OSMs and M2020 EDL Phasing Offsets and MRO LMST at EDL

	OSM-1 (OTM-54)	**OSM-2**	**OSM-3 (OTM-55)**	**M2020 EDL Target**
OD DCO for OSM	8/23/2020	12/07/2020	1/11/2021	
DCO Prior to M2020 EDL Target	179.3 days	73.2 days	38.4 days	
Average Drag ΔV Per Orbit	0.30 mm/s	0.25 mm/s	0.20 mm/s	
OD DCO Down-Track Timing Uncertainty (3-σ)	24.6 min	3.5 min	47.4 sec	
Post-OSM Down-Track Timing Uncertainty (3-σ)	21.8 min		27.1 sec	
OSM/EDL Date	9/02/2020	12/16/2020	1/20/2021	2/18/2021
OSM Execution Prior to M2020 EDL	169.3 days	64.3 days	29.2 days	
OSM Design ΔV	0.198930 m/s	*cancelled*	0.269661 m/s	
OSM Reconstructed ΔV	0.203020 m/s		0.270138 m/s	
M2020 EDL Relay Target File	ERTF-6		ERTF-10	ERTF-10
Predicted Phasing Correction[*]	44.3 min early		9.83 min late	$\pm$30 sec requirement
Predicted Phasing Offset Remaining[†]	24.0 min early		0.0 min	
Actual Phasing Offset (Pre-OSM)	64.5 min early		9.86 min late	
Actual Phasing Correction[‡]	45.6 min early		9.86 min late	**Achieved:**
Actual Phasing Offset (Post-OSM)	18.9 min early		0.52 sec late	**1.97 sec late**
3:30 PM LMST Target @ EDL (3:15–3:35 PM Req.)	3:30:27 PM		3:30:36 PM	**3:30:36 PM**

[*] Based on maneuver design (does not account for OD drift from DCO to OSM implementation or maneuver execution errors)
[†] Accounts for down-track timing uncertainty (3-σ)
[‡] Based on maneuver execution (accounts for OD drift from DCO to OSM implementation and maneuver execution errors)

After completion of OSM-1 a timing offset of about 19 minutes remained. This was to be partially corrected via OSM-2 initially scheduled for November 18, 2020. By then the phasing offset had decreased and crossed zero. This was due to dust activity and also the M2020 target changing. However, MRO went into safe mode briefly from October 13 to 16, following which OSM-2 was postponed to December 16, 2020. The safe mode did not have any significant effect on MRO's phasing offset. Eventually, OSM-2 was cancelled. OSM-3 was performed on January 20, 2021. This maneuver over-performed slightly by 0.2% placing MRO late by only 0.52 seconds from the target time. This was well within the then down-track timing uncertainty of about 27 seconds (29 days prior to M2020 EDL). The contingency phasing maneuver OSM-4 was unnecessary and hence cancelled. The MRO trajectory reconstruction done following the M2020 landing indicated that the spacecraft was late at the target location only by about 1.97 seconds. As expected, the atmospheric density variations and perhaps sub-optimal angular momentum desaturation maneuvers, etc., contributed to this slight change in the final phasing offset. Also the final achieved LMST at EDL was 3:30:36 PM (target was 3:30 PM) which was well within the requirement to be between 3:15 PM and 3:35 PM. A summary of the designed and reconstructed ΔVs of the maneuvers to support M2020 EDL and return MRO to science operations thereafter are given in Table 3. It includes maneuvers to achieve 3:30 PM LMST (OTM-53/OCM-4A), to phase to the EDL target (OTM-54 and OTM-55), and to partially recover the Ground Track Walk (GTW) control following M2020 EDL (OTM-56), and change MRO's LMST drift towards 3:10 PM (PSO) and recover the remaining GTW error (OTM-57/OCM-5). Reference 7 provides a detailed discussion of OTMs 53, 56 and 57.

Table 3: MRO Maneuver History for M2020 EDL Support and Science Operations Recovery

Maneuver	Maneuver Epoch (UTC SCET)	Orbital Apsis/ Node	Data Source	ΔV (mm/s)		Right Ascension (deg)		Declination (deg)		Duration (sec)	
				Value	$\lvert err\rvert$	Value	$\lvert err\rvert$	Value	$\lvert err\rvert$	Dur	$\lvert err\rvert$
OTM-52 (OCM-4)	12-Dec-2018 14:18:23	DEqX	Recon	1412.1	9.0	2.66	1.43	−60.47	0.03	20.1	0.2
			Design	1403.0		1.23		−60.50		20.3	
OTM-53 (OCM-4A)	23-Oct-2019 12:15:28	AEqX	Recon	2803.1	10.0	329.86	0.93	−30.76	0.38	39.3	0.4
			Design	2793.1		328.93		−30.39		39.7	
OTM-54 (OSM-1)	02-Sep-2020 13:41:38	Apo	Recon	203.0	4.1	47.71	0.16	−0.52	0.30	9.4	0.4
			Design	198.9		47.87		−0.82		9.0	
OSM-2	16-Dec-2020	*Cancelled*									
OTM-55 (OSM-3)	20-Jan-2021 14:36:48	Apo	Recon	270.1	0.5	300.03	0.15	−35.70	0.17	11.8	0.4
			Design	269.7		299.88		−35.53		12.2	
OSM-4	04-Feb-2021	*Contingency maneuver if ±30 sec requirement not met*									
OSM-4C	10-Feb-2021	*Contingency maneuver if ±30 sec requirement not met*									
M2020 EDL Target Time: 18-Feb-2021 20:37:56.8164 ET SCET											
OTM-56	14-Apr-2021 11:44:29	Peri	Recon	814.0	10.7	356.10	0.10	−33.85	0.40	11.7	0.1
			Design	803.3		356.20		−33.45		11.8	
OTM-57 (OCM-5)	09-Jun-2021 13:19:53	DEqX	Recon	19504.3	0.7	282.02	0.14	−35.59	0.02	271.0	4.4
			Design	19503.6		281.88		−35.61		275.4	

Atmospheric drag reduces MRO's orbital energy. This in turn reduces the orbital period compromising the ground track near repeat cycle. Pro-velocity maneuvers increase the semi-major axis, which extends the orbital period. Thus this maneuver approach also aided the GTW control, limited only by the phasing required by M2020 EDL support (see Figure 7). Reference 7 provides a more detailed discussion of the GTW maintenance strategy employed by MRO.

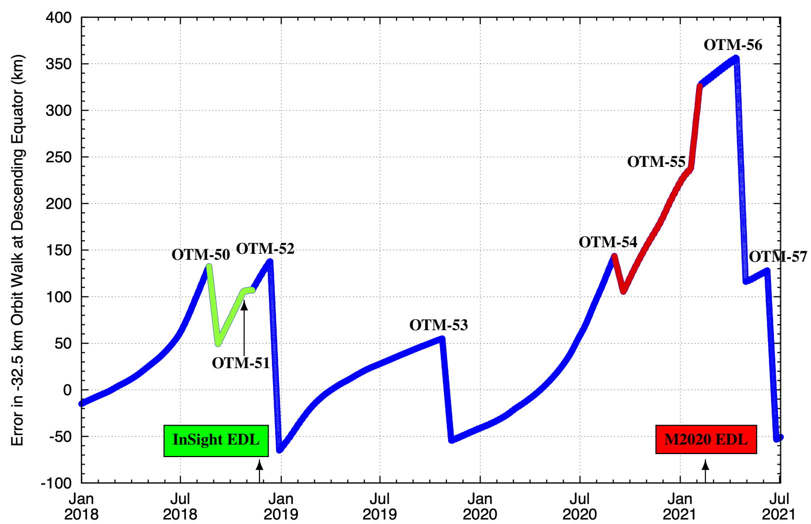


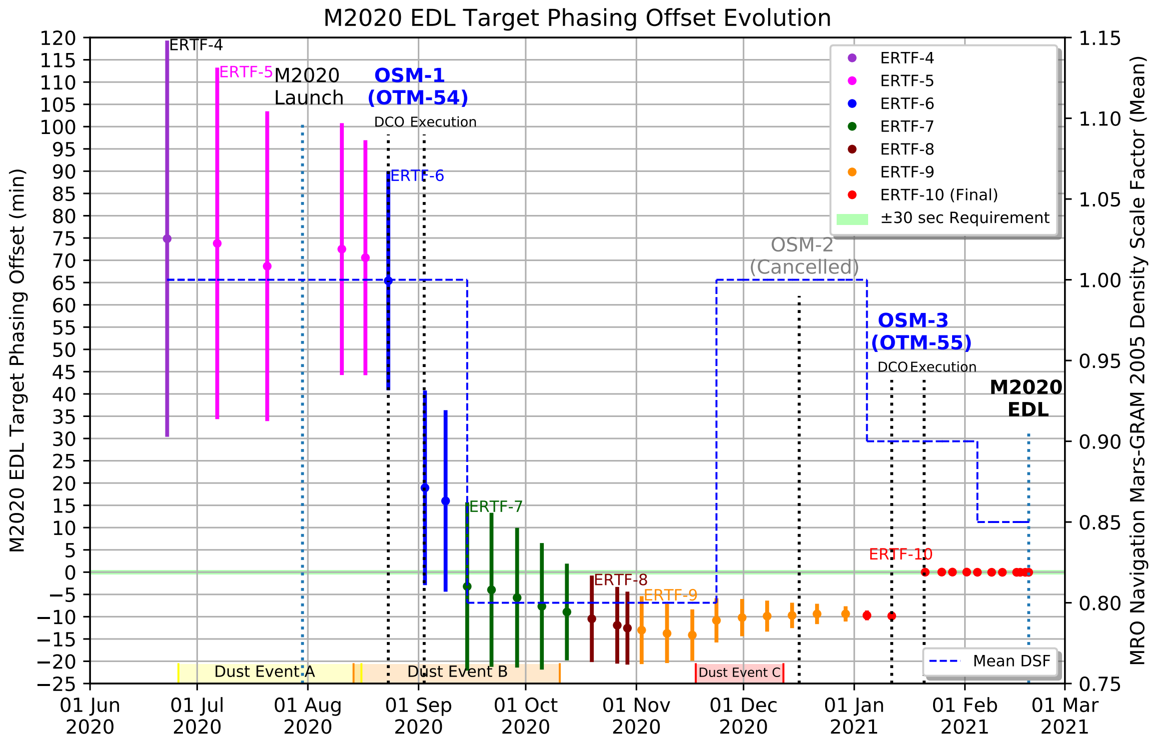
Figure 7: MRO Orbit Ground Track Walk Repeat Error from January 2018 – July 2021. *GTW control (blue), InSight EDL phasing (green), M2020 EDL phasing (red).*

Phasing Offset Evolution History

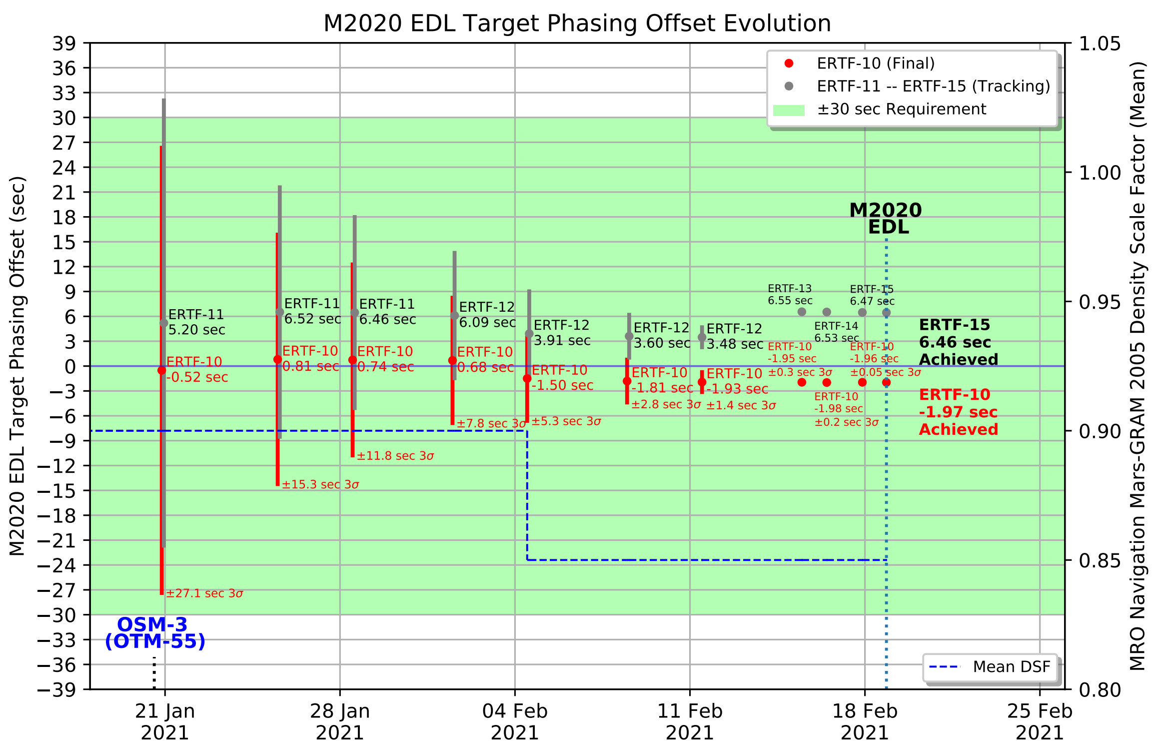
The MRO navigation team began actively tracking the phasing offset from the M2020 EDL target via the EDL target files (ERTFs) from the M2020 navigation team about a month prior to the M2020 launch (July 30, 2020). Post-launch ERTFs were provided to MRO per prescribed schedule agreed by the MRO and M2020 navigation teams. The MRO navigation team continued tracking the M2020 phasing offset after the launch until the day before EDL. This included removing some timing offset with the first phasing maneuver OSM-1 on September 2, 2020 and the remaining offset with the next phasing maneuver (OSM-3). The atmospheric density variations and other orbit determination inaccuracies were expected to affect the phasing offset. As the orbit determination of MRO is done at least twice per week, it was possible to periodically assess the current offset from the final desired target time. These offsets were reported to both the MRO and M2020 projects. The phasing offset values and associated navigation uncertainties are plotted in Figure 8. A negative sign in the offset indicates being late and a positive sign being early. For example, prior to the first phasing maneuver OSM-1, MRO was expected to arrive earlier at the desired target phase, while before the second phasing maneuver OSM-3, MRO was expected to arrive later at the desired target phase.

Also shown in Figure 8 are the different DSFs used in propagating the trajectory to estimate phasing offsets. The DSF adjusts the Mars-GRAM atmospheric model used for prediction. Since MRO's battery charging had become a concern following OTM-49 (September 13, 2017) the solar arrays did not get parked in spite of the near perihelion distances. Instead, they continued to track the Sun. This solar array configuration was different from earlier practice when a fixed configuration was utilized to help extend the gimbal life. This sun-track mode in turn had increased the effective area subjected to atmospheric drag, returning the phasing offsets to near expected levels. The first major dust activity, Dust Event-A started around June 25, 2020 and lasted until about August 16, 2020 as reported by the MCS payload team. Overlapping a bit with Dust Event-A, Dust Event-B started on August 13, 2020 and lasted until October 10, 2020. During these dust activities the DSF of 1.0 was used through OSM-1. Soon after, the DSF reduced to about 0.80. The next dust activity was a brief one; Dust Event-C occurred from November 7 to December 12, 2020. A DSF of 0.90 was used for the next maneuver design.

Table 4 gives the phasing offset values as computed with each orbit solution used in response to the ERTFs leading to M2020's arrival at Mars. The average DSF and 3-σ navigation timing uncertainty values are also provided for each phasing offset entry. Additionally, the table presents the OD data cutoff time and the number of days to the M2020 overflight time for each entry. OSM-1 execution along with OD drift from DCO to implementation removed about 46 minutes of the predicted phasing offset. The maneuver planning was based on the 24 minutes timing uncertainty at the time of the maneuver design DCO. The phasing offset started diminishing as the Dust Event-B started to subside soon after OSM-1 was performed. The next phasing maneuver OSM-2 was designed to remove part of the remaining offset. Effects on phasing from Dust Event-B was minimal due to reduced propagation time. However, the maneuver was first postponed from November 18 to December 16, 2020 but then was cancelled. OSM-3 was performed on January 20, 2021. This maneuver designed to remove the remaining phasing offset in its entirety of about 9.84 minutes (late) as the navigation uncertainty was about 47 seconds. The final reconstructed timing offset value of 1.97 seconds (late) with respect to the target used in the maneuver design (per ERTF-10) is highlighted in yellow at the bottom of the table. Note that ERTF-10 was the last target file used for MRO phasing; subsequent ERTF deliveries were used only for tracking purposes and the phasing offsets from those files are presented in the last column of the table. The final offset per the last



(a) Prior to Launch Through EDL



(b) Following OSM-3 Through EDL

Figure 8: Evolution of the M2020 EDL Target Phasing Offset

target file provided (ERTF-15) was 6.46 seconds (early). There were several changes after ERTF-10 in modeling for both MRO and M2020 which are reflected in ERTFs 11-15. With ERTF-10, OSM-3 was modeled as a burn centered at periapsis. However, OSM-3 was actually performed at apoapsis which changed the latitude target by about 0.3 deg and is reflected in ERTF-11. TCM-4 for M2020 was modeled through ERTF-12, but was cancelled and no longer modeled starting with ERTF-13. This caused the landing time to shift by ∼2.9 seconds.

Table 4: Evolution of MRO Phasing Offset from M2020 EDL Target

OD Data Cutoff (ET)	**Entry Relay Target File (ERTF)**	**Days to EDL from DCO**	**Avg. DSF**	**Avg. Drag ΔV Per Orbit**	**Navigation Timing Uncertainty (3σ)**	**EDL Phasing Offset** *Convention: + (early), − (late)*	
						Targeted	***Tracking (ERTF)***
22-JUN-2020 14:15:00	ERTF-4	241.3	1.00	0.30	44.47 min	+74.85 min	
06-JUL-2020 14:45:00	ERTF-5	227.2	1.00	0.30	39.45 min	+73.79 min	
20-JUL-2020 14:40:00	ERTF-5	213.2	1.00	0.30	34.77 min	+68.67 min	
10-AUG-2020 12:20:00	ERTF-5	192.3	1.00	0.30	28.27 min	+72.51 min	
17-AUG-2020 02:45:00	ERTF-5	185.7	1.00	0.30	26.37 min	+70.58 min	
23-AUG-2020 12:33:00	ERTF-6	179.3	1.00	0.30	24.57 min	+65.40 min	
OSM-1/OTM-54 (02-SEP-2020 13:42:47.5613 ET): designed to remove 44.3 min of offset (24.0 min remaining)							
02-SEP-2020 19:00:00	ERTF-6	169.1	1.00	0.30	21.84 min	+18.93 min	
08-SEP-2020 13:37:00	ERTF-6	163.3	1.00	0.30	20.37 min	+15.98 min	
14-SEP-2020 14:40:00	ERTF-7	157.2	0.80	0.30	18.89 min	−3.21 min	
21-SEP-2020 10:10:00	ERTF-7	150.4	0.80	0.30	17.29 min	−3.97 min	
28-SEP-2020 14:09:30	ERTF-7	143.3	0.80	0.30	15.68 min	−5.74 min	
05-OCT-2020 12:35:00	ERTF-7	136.3	0.80	0.30	14.20 min	−7.67 min	
12-OCT-2020 12:47:00	ERTF-7	129.3	0.80	0.25	10.85 min	−8.94 min	
19-OCT-2020 12:20:00	ERTF-8	122.3	0.80	0.25	9.71 min	−10.47 min	
26-OCT-2020 15:10:00	ERTF-8	115.2	0.80	0.25	8.61 min	−11.93 min	
29-OCT-2020 11:35:00	ERTF-8	112.4	0.80	0.25	8.19 min	−12.57 min	
02-NOV-2020 11:15:00	ERTF-9	108.4	0.80	0.25	7.62 min	−13.01 min	
09-NOV-2020 13:46:00	ERTF-9	101.3	0.80	0.25	6.65 min	−13.75 min	
16-NOV-2020 15:44:00	ERTF-9	94.2	0.80	0.25	5.76 min	−14.12 min	
23-NOV-2020 09:55:00	ERTF-9	87.4	1.00	0.25	4.96 min	−10.82 min	
30-NOV-2020 14:30:00	ERTF-9	80.3	1.00	0.25	4.18 min	−10.20 min	
07-DEC-2020 14:39:00	ERTF-9	73.2	1.00	0.25	3.48 min	−9.87 min	
14-DEC-2020 14:15:00	ERTF-9	66.3	1.00	0.25	2.85 min	−9.72 min	
21-DEC-2020 14:00:00	ERTF-9	59.3	1.00	0.25	2.28 min	−9.38 min	
29-DEC-2020 14:00:00	ERTF-9	51.3	1.00	0.25	1.71 min	−9.37 min	
04-JAN-2021 13:23:00	ERTF-10	45.3	0.90	0.20	1.10 min	−9.71 min	
11-JAN-2021 12:05:00	ERTF-10	38.4	0.90	0.20	47.4 sec	−9.84 min	
OSM-3/OTM-55 (20-JAN-2021 14:37:57.8233 ET): designed to remove remaining offset							
20-JAN-2021 20:52:00	ERTF-10	29.0	0.90	0.20	27.1 sec	−0.52 sec	*ERTF-11: +5.20 sec*
25-JAN-2021 12:10:00	ERTF-10	24.4	0.90	0.15	15.3 sec	+0.81 sec	*ERTF-11: +6.52 sec*
28-JAN-2021 12:06:30	ERTF-10	21.4	0.90	0.15	11.8 sec	+0.74 sec	*ERTF-11: +6.46 sec*
01-FEB-2021 12:00:00	ERTF-10	17.4	0.90	0.15	7.8 sec	+0.68 sec	*ERTF-12: +6.09 sec*
04-FEB-2021 11:41:00	ERTF-10	14.4	0.85	0.15	5.3 sec	−1.50 sec	*ERTF-12: +3.91 sec*
08-FEB-2021 11:38:00	ERTF-10	10.4	0.85	0.15	2.8 sec	−1.81 sec	*ERTF-12: +3.60 sec*
11-FEB-2021 11:34:30	ERTF-10	7.4	0.85	0.15	1.4 sec	−1.93 sec	*ERTF-12: +3.48 sec*
15-FEB-2021 11:25:00	ERTF-10	3.4	0.85	0.15	0.3 sec	−1.95 sec	*ERTF-13: +6.55 sec*
16-FEB-2021 11:20:00	ERTF-10	2.4	0.85	0.15	0.2 sec	−1.98 sec	*ERTF-14: +6.53 sec*
17-FEB-2021 21:30:00	ERTF-10	1.0	0.85	0.15	0.05 sec	−1.96 sec	*ERTF-15: +6.47 sec*
M2020 EDL Phasing Target Reconstruction			**0.85**	**0.15**	**per ERTF-10:**	**−1.97 sec**	***ERTF-15: +6.46 sec***

MRO provided M2020 EDL support using “bent-pipe” relay capability. This involved MRO to acquire data from the incoming lander and transmit to Earth in near-realtime which required the spacecraft to do tracking while slewing. Delivering the spacecraft at the desired atmospheric entry point for M2020 EDL to about 1.97 seconds was a significant accomplishment for navigation as it placed MRO at a near-perfect position for the execution of its special "track and slew" sequence in which the HGA tracked the earth while a slew maneuver was in progress. This sequence designed for bent-pipe telecommunications and HiRISE imaging was the first ever flight demonstration of this capability for MRO.[5] During the EDL support MRO spacecraft attitude control was maintained by gyros, returning to star tracker control only after EDL was complete.

MARS 2020 LANDING

The Perseverance rover successfully landed on Mars on February 18, 2021. The expected times of entry and touch down were 20:37:59 ET and 20:44:51 ET, respectively, per ERTF-15. By this time the Mars atmospheric density was at low levels resulting in very low drag ΔV as seen in Figure 9. The drag ΔV averaged over 39 orbits during the M2020 EDL period is shown in red in Figure 9 (Mars Year 35). For comparison, the drag ΔV during a similar time frame in the previous Mars year (MY 34) is indicated in blue. Also shown are the periods of the Dust Events A, B and C.

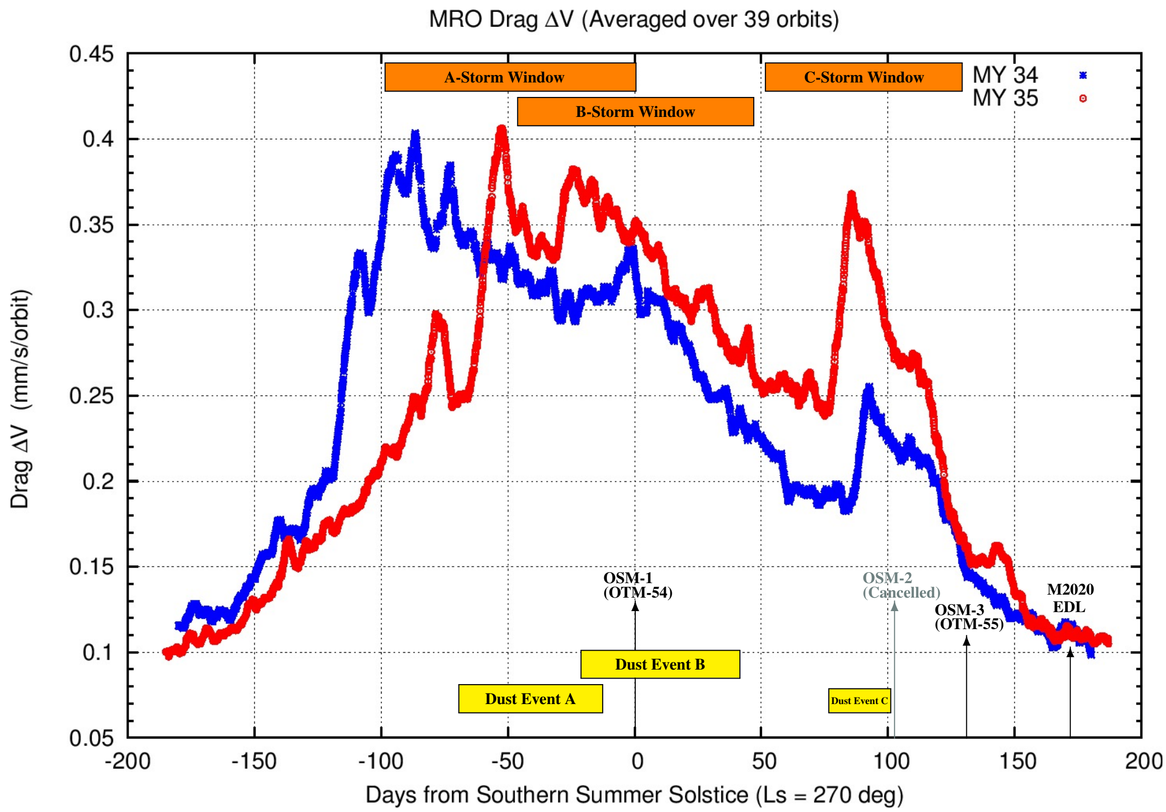


Figure 9: MRO Drag ΔV Per Orbit. *Days from Southern Summer Solstice (Day 0 corresponds to L_s = 270°)*

Planned Mars 2020 Overflights

The MRO project was expected to provide surface relay support after M2020 EDL. MRO was to remain in its current orbit for at least seven sols. Table 5 shows the M2020 overflight profile in the first seven days following landing (e.g., pass start times and durations, maximum elevation angles of each pass and corresponding times, etc.). Overflights following EDL (Pass #0) with pass durations of at least 10 minutes and maximum elevation angles of at least 30 degrees are highlighted in yellow. One or more overflight opportunities were available roughly every 12 hours following landing, with a majority of back-to-back orbits providing overflights (day/day and night/night pairs). Two day passes, Passes #1 and #20 in the table, were used to take the HiRISE images of the landing site shown in Figure 12.

Table 5: Predicted M2020 Overflights in First Week of Support

Pass #	Pass Start (Relative to M2020 Landing)	Pass Start Time (ET)	Pass Length (min)	Max Elevation Angle (deg)	Max Elevation Time (ET)	MRO Off-Nadir Angle (deg)	Day/Night Pass
0	-0.1 hrs (-0.00 days)	18-FEB-2021 20:40:03.2727	13.37	30.91	18-FEB-2021 20:46:31.6003	-52.54	Day
1	11.9 hrs (0.49 days)	19-FEB-2021 08:37:17.9989	13.93	87.09	19-FEB-2021 08:44:28.2091	-2.65	Night
2	24.2 hrs (1.01 days)	19-FEB-2021 20:57:14.8033	13.90	70.97	19-FEB-2021 21:03:58.8235	-17.61	Day
3	36.2 hrs (1.51 days)	20-FEB-2021 08:54:56.3212	13.58	37.42	20-FEB-2021 09:01:55.1951	-47.26	Night
4	38.1 hrs (1.59 days)	20-FEB-2021 10:49:13.7116	6.41	2.73	20-FEB-2021 10:52:26.2472	67.39	Night
5	48.5 hrs (2.02 days)	20-FEB-2021 21:14:51.5075	13.74	49.29	20-FEB-2021 21:21:31.2045	37.13	Day
6	50.5 hrs (2.10 days)	20-FEB-2021 23:11:59.8573	2.39	0.35	20-FEB-2021 23:13:03.9524	-67.53	Day
7	60.5 hrs (2.52 days)	21-FEB-2021 09:12:59.5695	12.45	18.05	21-FEB-2021 09:19:21.6837	-61.52	Night
8	62.3 hrs (2.60 days)	21-FEB-2021 11:04:57.9434	10.43	9.23	21-FEB-2021 11:10:14.4959	65.89	Night
9	72.8 hrs (3.03 days)	21-FEB-2021 21:32:55.6888	12.87	22.99	21-FEB-2021 21:39:10.7040	58.35	Day
10	74.7 hrs (3.11 days)	21-FEB-2021 23:25:58.1784	9.30	6.31	21-FEB-2021 23:30:27.2294	-66.73	Day
11	84.8 hrs (3.53 days)	22-FEB-2021 09:31:35.6404	10.22	8.32	22-FEB-2021 09:36:46.4864	-66.14	Night
12	86.6 hrs (3.61 days)	22-FEB-2021 11:21:38.9282	12.50	19.23	22-FEB-2021 11:28:01.3684	60.91	Night
13	97.1 hrs (4.05 days)	22-FEB-2021 21:51:28.4862	11.11	11.24	22-FEB-2021 21:56:52.1601	65.04	Day
14	99.0 hrs (4.12 days)	22-FEB-2021 23:42:04.2363	11.96	14.86	22-FEB-2021 23:47:51.4325	-63.33	Day
15	109.1 hrs (4.55 days)	23-FEB-2021 09:51:20.0158	5.48	1.86	23-FEB-2021 09:54:03.8943	-67.46	Night
16	110.9 hrs (4.62 days)	23-FEB-2021 11:38:41.8995	13.59	39.72	23-FEB-2021 11:45:40.1112	45.48	Night
17	121.4 hrs (5.06 days)	23-FEB-2021 22:10:47.8222	7.80	4.03	23-FEB-2021 22:14:33.6401	67.20	Day
18	123.2 hrs (5.13 days)	23-FEB-2021 23:58:48.2100	13.34	30.47	24-FEB-2021 00:05:15.6463	-52.89	Day
19	135.2 hrs (5.63 days)	24-FEB-2021 11:56:01.3868	13.94	88.24	24-FEB-2021 12:03:11.9244	-1.57	Night
20	147.5 hrs (6.15 days)	25-FEB-2021 00:15:58.7370	13.88	69.91	25-FEB-2021 00:22:42.2326	-18.59	Day
21	159.5 hrs (6.65 days)	25-FEB-2021 12:13:38.8113	13.61	37.95	25-FEB-2021 12:20:38.4500	-46.80	Night
22	161.4 hrs (6.72 days)	25-FEB-2021 14:07:58.9848	6.33	2.67	25-FEB-2021 14:11:09.1907	67.39	Night
23	171.8 hrs (7.16 days)	26-FEB-2021 00:33:34.4198	13.73	49.95	26-FEB-2021 00:40:13.9208	36.55	Day
24	173.8 hrs (7.24 days)	26-FEB-2021 02:30:55.5100	1.97	0.25	26-FEB-2021 02:31:47.1222	-67.55	Day

Mars 2020 Landing Site

The M2020 landing on Mars was very successful following the final M2020 maneuver TCM-3. The Perseverance rover landed ∼1.7 km from the landing target. The successful performance of the Terrain Relative Navigation (TRN) system selected a safe landing location inside Jezero Crater to maximize the probability of success and was key to a successful landing of the rover. Perseverance landed within 5 m from the target selected by the TRN system.[8]

The HiRISE camera took an image one day after landing that revealed four separate locations for the Perserverance rover, the parachute and back shield, the descent stage (sky crane), and the heat shield (Figure 12a). Figure 12b shows a HiRISE image taken one week after landing with the Perserverance rover seen in the center of the image. The overflight information provided by the MRO Navigation Team (see Table 5) also aided in the planning of these images.

Based on the final MRO predicted trajectory during the EDL phase, Figure 10 shows the range between MRO and M2020 during EDL. The plot indicates the predicted times and corresponding ranges at entry and landing per ERTF-15, the final verification of the M2020 EDL target, as well as the predicted parachute deploy time (∼240 seconds after entry). In Figure 11 the descent stage can be seen with the Perseverance rover and parachute as it falls through the Mars atmosphere.

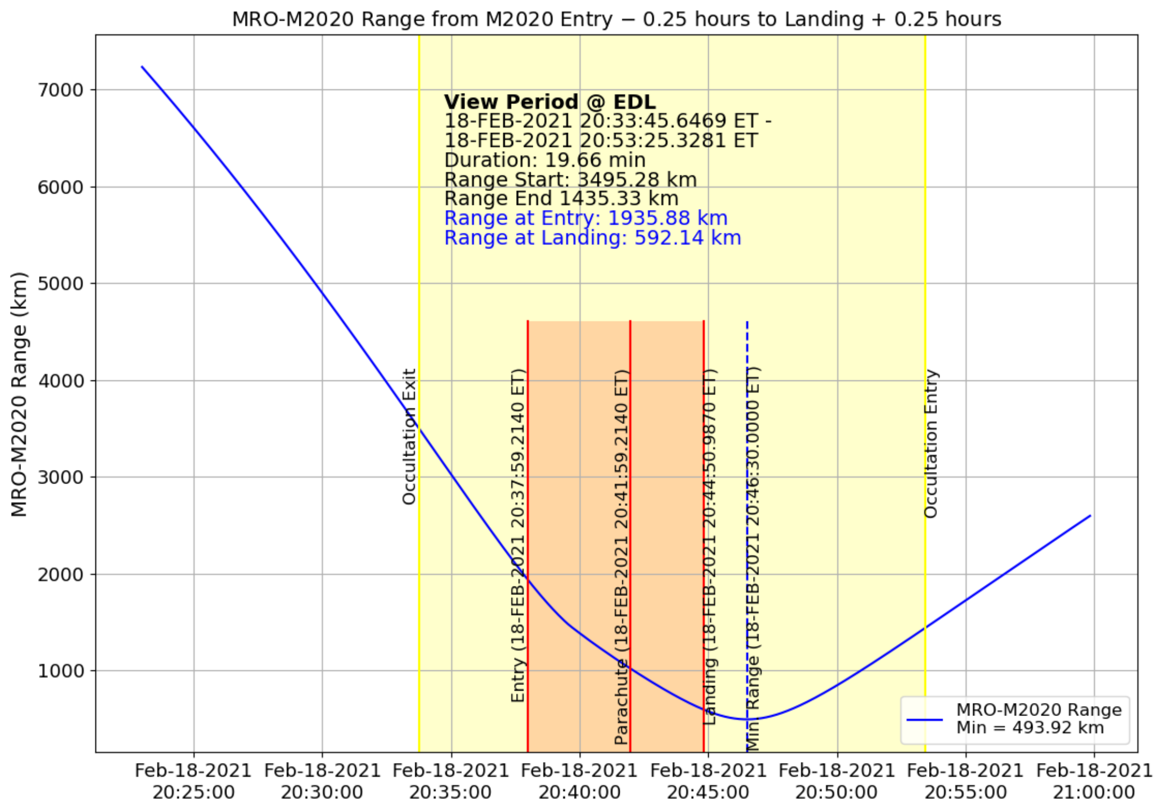


Figure 10: MRO-M2020 Range

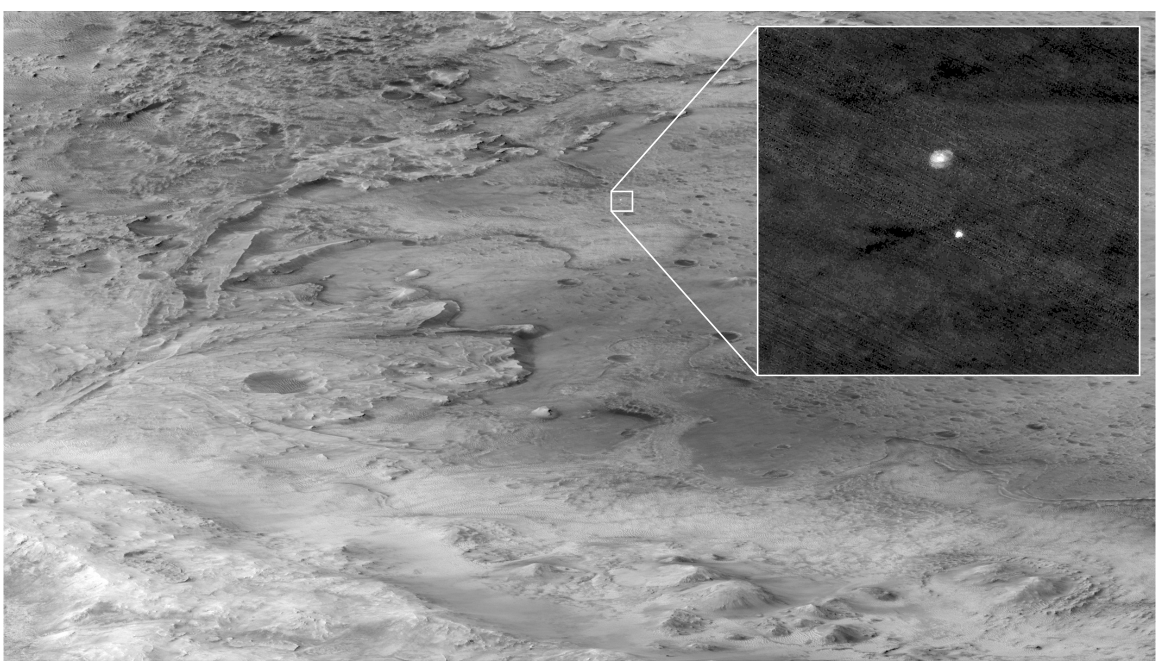
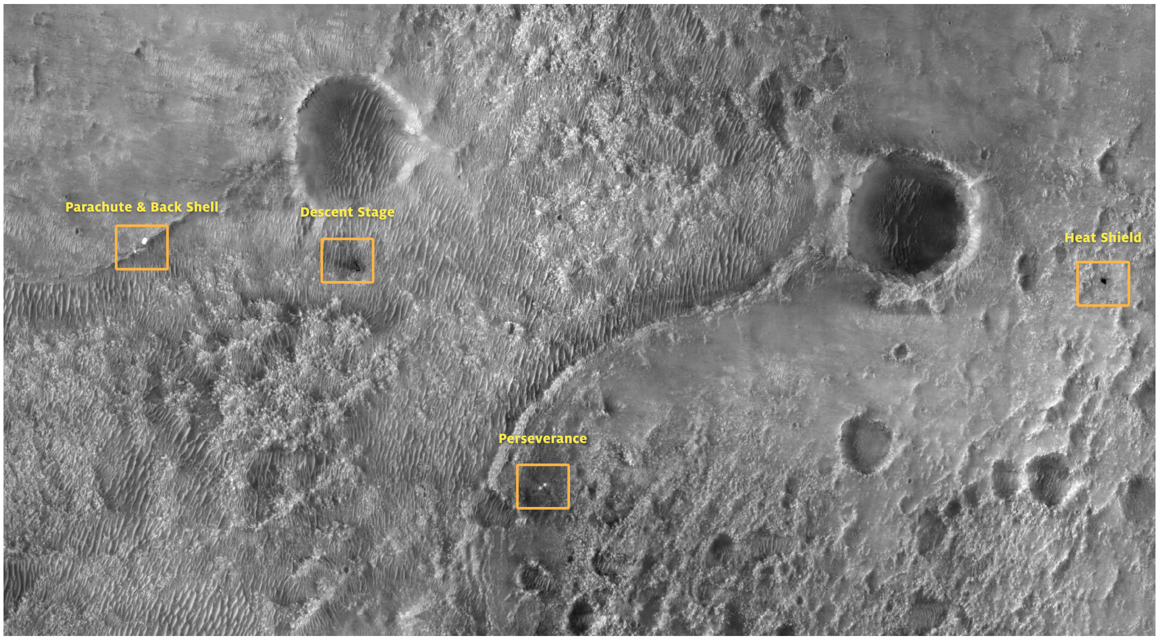
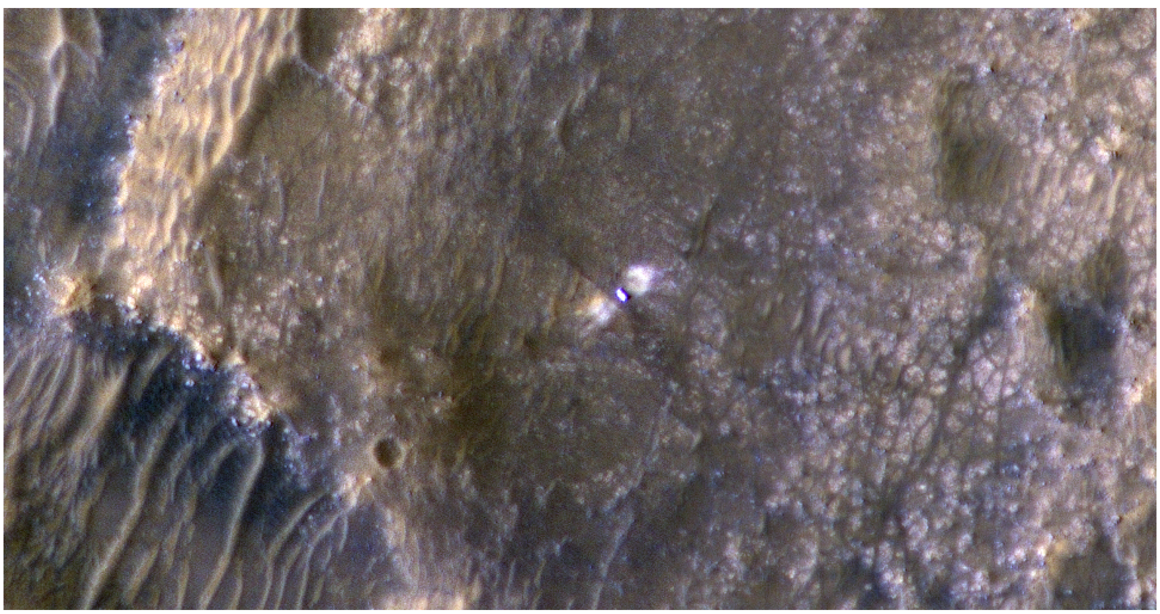


Figure 11: Descent Stage with Perseverance and Parachute Taken by HiRISE Camera on February 18, 2021. Source: NASA/JPL-Caltech/University of Arizona/LPL.



(a) An annotated image of the surface of Mars, taken by the HiRISE camera on February 19, 2021, one day after M2020 landing. The annotations display the locations of the Perseverance rover and hardware (heat shield, back shell, descent stage, and parachute).



(b) Image of the M2020 landing site with the Perservance rover (center of image) Taken by HiRISE on February 25, 2021.

Figure 12: Images of the M2020 Landing Site Taken by HiRISE on February 19 and 25, 2021. Source: NASA/JPL-Caltech/University of Arizona/LPL.

RETURN TO MRO PRIMARY SCIENCE ORBIT (PSO) AFTER M2020 EDL SUPPORT

Since GTW maneuvers had not been performed for a long time due to M2020 EDL support, MRO's GTW error had increased outside the mission requirement of ± 60 km for a brief period of time, as can be seen in Figure 7. It had accumulated about +333 km of GTW error by the time M2020 EDL was completed. It was the largest GTW error MRO had ever reached as compared to the Comet Siding Spring Risk mitigation effort when it drifted to about +240 km. M2020's phasing needs had prevented MRO's GTW control maneuvers. In addition, MRO's orbits had started to cluster, limiting the HiRISE team from acquiring stereo images. This became a significant problem in late 2020. Thus, it was critically important to recover the ground track control as soon as possible. Earlier, OTM-56 was planned for March 14, 2021 to correct the GTW and would have included an inclination change component for changing MRO's LMST. M2020's post-landing desire for MRO to go to 4:30 PM LMST for relay efficiency conflicted with MRO's science objective of returning to 3:10 PM. In order to accommodate the pending decision by NASA HQ on MRO's future LMST, the MRO project postponed the inclination change. OTM-56 with a ΔV of 0.8 m/s was performed on April 14, 2021 to only partially recover GTW control by reducing the +355 km GTW error to +120 km. Following M2020 EDL, MRO's orbit also continued to drift to a later LMST. Meanwhile NASA HQ made its decision and advised MRO not to go to 4:30 PM LMST. With a ΔV of 19.5 m/s, OTM-57 (OCM-5) was successfully executed on June 9, 2021 by which time the LMST had reached about 3:41 PM. OTM-57 was the largest maneuver performed since the transition from the aerobraking phase to the PSP in late 2006. The maneuver included a large out-of-plane component to change the nodal drift such that an LMST of 3:10 PM would be achieved by November 17, 2021 at which time another inclination maneuver OCM-6 would arrest the drift. OTM-57 also included an in-plane component to fully restore the GTW by targeting to -60 km GTW error. Reference 7 describes the two maneuvers outlined above, OTM-56 and OTM-57 (OCM-5), that were used to reestablish the PSO along with OCM-6 which is scheduled for November 17, 2021.

CONCLUSION

MRO successfully provided relay support to M2020 during its EDL phase. Using OTM-53 (OCM-4A) on October 23, 2019, the MRO navigation team had targeted an LMST of 3:30 PM for M2020 EDL support. The final achieved LMST at EDL was 3:30:36 PM, well within the requirement to be between 3:15 PM and 3:35 PM. The successful support was also largely due to an accurate phasing that MRO achieved and the first-time use of a bent-pipe relay capability.[5] Following the M2020 landing, MRO continues to provide excellent relay support for M2020's surface operations. In addition, MRO's HiRISE camera made observations and images of the different landed parts of the Perseverance rover, including the parachute, back shell and heat shield. The navigation plan to phase MRO to the prescribed M2020 EDL target location was successfully implemented with the executions of two maneuvers, OSM-1 and OSM-3 (OSM-2 was cancelled in favor of OSM-3). The predicted phasing offset following OSM-3 of 0.52 seconds late from the target was well within the M2020 phasing requirement of ± 30 seconds and MRO navigation's 3-σ timing uncertainty of 27.1 seconds, leading to the cancellation of OSM-4 and the contingency maneuver OSM-4C. Ultimately, MRO was only about 1.97 seconds late from its intended target (per ERTF-10), despite three dust events and the OD drift and execution errors from OSM-3, the final phasing maneuver performed. However, the actual final offset was 6.46 seconds earlier than the target provided in ERTF-15, which incorporated M2020's final phasing target. This phasing accuracy can be better appreciated in comparison to the 9.0 seconds timing accuracy when supporting

MSL EDL in August 2012[2] and 8.4 seconds when supporting InSight EDL in November 2018.[4] Additionally, the MRO navigation team provided the overflight information which assisted in the efforts to image the landed parts of the M2020 mission. In summary, the navigation team was able to achieve the M2020 EDL relay target well within the ±30 seconds requirement, directly resulting in the successful relay support during EDL.

ACKNOWLEDGMENTS

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APPENDIX: EDL RELAY TARGET FILES

Coordination between the MRO and M2020 navigation teams was established prior to the launch of M2020. The M2020 navigation team provided EDL Relay Target File (ERTF) files which included the EDL target time and corresponding latitude (see Reference 11). In return, MRO supplied M2020 the predicted MRO trajectories based on current orbit solutions through the M2020 EDL support period. Table 6 presents the ERTF history. ERTF-10 (highlighted in Table 6) was used for designing OSM-3, the final OSM performed to phase MRO to the M2020 EDL target.

Table 6: History of M2020 EDL Relay Targets for MRO Phasing

ERTF	Delivery Date	Days to EDL	MRO Relay Targets (2000 IAU Mars Fixed)				Comments
			18-Feb-2021 Epoch (ET)	Latitude (deg)	LMST*	Mean Anomaly Phasing (deg)*	
1	28-Aug-2018	905	20:25:47.3728	−4.0256	15:30:02	98.0	Launch − 2 years
2	23-Apr-2019	667	20:26:43.0150	−9.8215	15:30:05	91.5	Launch − 15 months
3	17-Jul-2019	582	20:26:42.9550	−10.8077	15:30:09	86.0	Launch − 12 months
4	21-Jan-2020	394	20:26:43.4450	−9.9799	15:30:05	74.0	Launch − 6 months
5	13-Jul-2020	220	20:37:59.2899	−9.8846	15:30:12	80.0	Launch − 17 days
6	19-Aug-2020	183	20:37:59.3403	−10.2413	15:30:34	71.0	TCM-1 executed on 15-Aug-2020, used for OSM-1
7	17-Sep-2020	154	20:38:02.0594	−9.9500	15:30:43	74.0	OSM-1 executed on 02-Sep-2020
8	16-Oct-2020	125	20:38:02.2367	−9.6600	15:30:44	74.0	TCM-2 executed on 30-Sep-2020
9	02-Nov-2020	108	20:38:02.2367	−9.4355	15:30:44	74.0	
10	04-Jan-2021	45	20:37:56.8164	−9.6220	15:30:40	74.0	TCM-3 executed on 18-Dec-2020, used for OSM-3
11	14-Jan-2021	35	20:37:56.4130	−9.9502	15:30:40	74.0	TCM-4 modeled on 10-Feb-2021, OSM-3 changed from peri. to apoapsis (latitude shifted by ∼0.3 deg)
12	28-Jan-2021	21	20:37:56.3757	−9.9360	15:30:40	74.0	TCM-4 modeled, OSM-3 executed on 20-Jan-2021
13	12-Feb-2021	6	20:37:59.2436	−9.9482	15:30:40	74.0	TCM-4 cancelled (landing time shifted by ∼2.9 sec)
14	16-Feb-2021	2	20:37:59.2477	−9.9481	15:30:40	74.0	
15	17-Feb-2021	1	20:37:59.2140	−9.9457	15:30:40	74.0	

* Supplemental information (not targeted for MRO phasing)

ERTF-10 was provided to the MRO navigation team for the final phasing maneuver design while ERTFs 11 – 15 were used for tracking the offset and incorporated the effects of the change of OSM-3 modeling, OSM-3 execution, and cancellation of TCM-4. As seen in Figure 13, these files contain the requested relay target as well as the predicted entry and landing epochs and coordinates.

```
---------------------------------------------------------------
EDL RELAY TARGETS FILE (ERTF)
---------------------------------------------------------------
Data generated on Mon Jan  4 14:53:39 2021 by J. Kangas,
NASA Jet Propulsion Laboratory

M2020 SPK File:
        m2020_trajCEDLS-6DOF_od068v1_L4_20210218-20210219.bsp
MRO SPK File: m2020_spk_mro_ertf-10_od068v1_74.bsp

************************************************************
* MRO RELAY TARGETS
* Epoch                         : 18-FEB-2021 20:37:56.8164 ET
* LMST (Asc.Eq.Cross)           : 15:30:40
* Latitude (2000 IAU Mars Fixed) : -9.6220 deg
************************************************************

M2020 Data (2000 IAU Mars Fixed)
Entry Epoch              : 18-FEB-2021 20:37:56.8164 ET
     Entry Latitude      : 20.7753 deg
     Entry Longitude     : 66.7613 deg
     Entry Radius        : 3522.2000 km
     Entry Range to MRO  : 1934.6677 km
Landing Epoch            : 18-FEB-2021 20:44:48.6730 ET
     Landing Latitude    : 18.4552 deg
     Landing Longitude   : 77.4112 deg
     Landing Radius      : 3391.9670 km
     Landing Range to MRO: 592.5212 km
MRO Data - Keplerian Osculating Elements (2000 IAU Mars Pole)
Entry Epoch              : 18-FEB-2021 20:37:56.8164 ET
     Semimajor Axis      : 3663.7693 km
     Eccentricity        : 0.009255
     Inclination         : 92.8182 deg
     RAAN                : 271.5197 deg
     Arg. of Periapsis   : 275.3434 deg
     Mean Anomaly        : 74.0001 deg
     True Anomaly        : 75.0228 deg
MRO Data - Spherical Coordinates (2000 IAU Mars Fixed)
Entry Epoch              : 18-FEB-2021 20:37:56.8164 ET
     Target Latitude     : -9.6220 deg
     Target Longitude    : 73.9461 deg
     LMST (Asc.Eq.Cross) : 15:30:40
     LTST (Asc.Eq.Cross) : 14:52:44
Landing Epoch            : 18-FEB-2021 20:44:48.6730 ET
     MRO Lat. at Landing    : 12.4029 deg
     MRO Lon. at Landing    : 71.1750 deg
```

(a) M2020 ERTF-10 (Used for Final MRO Phasing Maneuver)

```
---------------------------------------------------------------
EDL RELAY TARGETS FILE (ERTF)
---------------------------------------------------------------
Data generated on Wed Feb 17 07:53:26 2021 by J. Kangas,
NASA Jet Propulsion Laboratory

M2020 SPK File:
        m2020_trajCEDLS-6DOF_od109v1_NOBURN_20210218-20210219.bsp
MRO SPK File: m2020_spk_mro_ertf-15_od109v1_74.bsp

************************************************************
* MRO RELAY TARGETS
* Epoch                         : 18-FEB-2021 20:37:59.2140 ET
* LMST (Asc.Eq.Cross)           : 15:30:40
* Latitude (2000 IAU Mars Fixed) : -9.9457 deg
************************************************************

M2020 Data (2000 IAU Mars Fixed)
Entry Epoch              : 18-FEB-2021 20:37:59.2140 ET
     Entry Latitude      : 20.8274 deg
     Entry Longitude     : 66.7975 deg
     Entry Radius        : 3522.2000 km
     Entry Range to MRO  : 1956.4132 km
Landing Epoch            : 18-FEB-2021 20:44:50.9870 ET
     Landing Latitude    : 18.4548 deg
     Landing Longitude   : 77.4213 deg
     Landing Radius      : 3391.9579 km
     Landing Range to MRO: 605.5539 km
MRO Data - Keplerian Osculating Elements (2000 IAU Mars Pole)
Entry Epoch              : 18-FEB-2021 20:37:59.2140 ET
     Semimajor Axis      : 3663.7893 km
     Eccentricity        : 0.008950
     Inclination         : 92.8183 deg
     RAAN                : 271.5210 deg
     Arg. of Periapsis   : 275.0534 deg
     Mean Anomaly        : 73.9999 deg
     True Anomaly        : 74.9888 deg
MRO Data - Spherical Coordinates (2000 IAU Mars Fixed)
Entry Epoch              : 18-FEB-2021 20:37:59.2140 ET
     Target Latitude     : -9.9457 deg
     Target Longitude    : 73.9541 deg
     LMST (Asc.Eq.Cross) : 15:30:40
     LTST (Asc.Eq.Cross) : 14:52:44
Landing Epoch            : 18-FEB-2021 20:44:50.9870 ET
     MRO Lat. at Landing    : 12.0737 deg
     MRO Lon. at Landing    : 71.1839 deg
```

(b) M2020 ERTF-15 (Final Verification)

Figure 13: M2020 ERTFs Used for MRO Final Phasing and Offset Tracking

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