(Preprint) AAS 15-532

MARS RECONNAISSANCE ORBITER NAVIGATION STRATEGY FOR DUAL SUPPORT OF INSIGHT AND EXOMARS ENTRY, DESCENT AND LANDING DEMONSTRATOR MODULE IN 2016

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Mars Reconnaissance Orbiter (MRO) will support NASA's InSight Mission and ESA's ExoMars Entry, Descent and Landing Demonstrator Module (EDM) in the fall of 2016 when both landers arrive at Mars. MRO provided relay support during the Entry, Descent and Landing (EDL) sequences of Mars Phoenix Lander in 2008 and the Mars Science Laboratory in 2012. Unlike these missions, MRO will coordinate between two EDL events separated by only three weeks: InSight on September 28, 2016 and EDM on October 19, 2016. This paper describes MRO Navigation's maneuver strategy to move MRO's ascending node to meet the InSight EDL phasing requirement and support EDM.

INTRODUCTION

Mars Reconnaissance Orbiter (MRO), now in its third extended mission, is expected to provide telecommunication relay support to both NASA's Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) Mission and ESA's ExoMars EDM in the fall of 2016. This will include providing telecom relay link to InSight during its Entry, Descent and Landing (EDL) phase and relay during its surface operations. Also, MRO is expected to lend support to EDM either during EDL phase or the first overflight during four days of surface operations relay support. The EDL support of EDM was a strong consideration earlier and is the basis of the analysis reported in this paper. However, currently the overflight support possibility is in the forefront. The analysis described in the paper is still applicable to both scenarios. Previously, MRO provided relay support during the EDL sequences of other spacecraft such as the Mars Phoenix Lander in May 2008,[1,2] and more recently, the Mars Science Laboratory (MSL) in August 2012.[3,4] However, unlike these previous missions, the InSight and EDM missions are expected to land on Mars just three weeks apart; InSight is scheduled to land on September 28, 2016, followed by EDM on October 19, 2016. This poses a unique challenge for MRO to position itself at two different phasing locations separated by a short duration of time.

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This paper documents MRO Navigation's maneuver strategy to move the spacecraft's ascending node to meet the InSight EDL phasing requirement and support EDM EDL or EDM's first overflight. It also presents an overview of the MRO spacecraft and its primary science and mission objectives, as well as describe its past support for the Phoenix and MSL EDL sequences and its planned support for the upcoming InSight and EDM landings. Additionally, the baseline strategy for changing the Local Mean Solar Time (LMST) to 2:30 PM at InSight EDL via Orbit Change Maneuvers (OCMs) will be described. This maneuver strategy also involves returning MRO to the Primary Science Orbit (PSO) with 3:00 PM LMST while staying above the Local True Solar Time (LTST) minimum requirement of 2:00 PM. With atmospheric drag ΔVs during the InSight and EDM EDLs anticipated to be much larger than that experienced at the time of MSL EDL,[4] meeting both InSight and EDM timing requirements will present a challenge for MRO Navigation. These and other support challenges will be detailed in this manuscript.

MISSION OVERVIEW

MRO was launched from Cape Canaveral Air Force Station on August 12, 2005 and has just completed 10 years of operation. After an interplanetary cruise of seven months, it reached Mars on March 12, 2006. Following the Mars Orbit Insertion (MOI) and a period of aerobraking, MRO conducted Primary Science Phase (PSP), Extended Science Phase (ESP), and subsequently, two Extended Missions (EM1 and EM2) of operation. MRO is currently operating in the Extended Mission 3 (EM3). The MRO Navigation Team has been providing mission support through all these mission phases by performing Orbit Determination (OD) of MRO's trajectory and maintaining the Primary Science Orbit (PSO) through propulsive maintenance maneuvers.

MRO Spacecraft

The spacecraft bus built by Lockheed Martin provides a stable platform for the payload suite of 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 as well as surface and subsurface conditions. Among MRO's instruments, high fidelity imagery is performed using the High Resolution Imaging Science Experiment (HiRISE) camera. This key asset is able to provide imaging of orbiting or landed asset on Mars as well as mission support observations of possible future landing site locations. During the Primary and Extended missions, HiRISE and other science instruments were used primarily for nadir-pointed observations. MRO can also perform off-nadir targeted observations by rolling about the spacecraft flight direction (30 degrees maximum roll angle, seasonally-dependent). Pointing errors are minimized by performing periodic updates of the onboard spacecraft ephemeris.

An engineering payload, the Electra Proximity Link Payload, is able to provide relay telecommunication support in the UHF frequency range. The Electra transceiver allows the spacecraft to relay commands from Earth to the Mars Surface and to return science and engineering data from the surface back to Earth. It can collect Doppler data for surface navigation and support Mars approach and EDL navigation by other missions. Electra will provide near omni-directional coverage of surface assets via its UHF antenna and has a 60-degree half-angle field of view. However, it can only communicate with one surface asset at a time and does not have any X-band capability.[5]

MRO Primary Science Orbit

The MRO PSO is designed to satisfy science and mission requirements; the spacecraft is flown in an orbit designed to optimize the science instruments performance. The MRO PSO is defined by three key characteristics:

- Near-repeat ground track walk (GTW) is every 17-day, 211 orbit (short-term repeat) MRO targeting cycle, exact repeat is after 4602 orbits. The nominal GTW is 32.45811 km West each 211 orbit cycle.
- Periapsis is frozen about the Mars South Pole. The mean eccentricity – mean argument of periapsis ($e - \omega$) space is used to track this frozen condition.
- Sun-synchronous orbit ascending node at 3:00 PM $\pm$ 15 minutes Local Mean Solar Time (LMST) (daylight equatorial crossing).

MRO Orbit Maintenance

MRO Navigation has maintained the PSO via propulsive maneuvers, or Orbit Trim Maneuvers (OTMs). OTMs are typically performed in one of two standard maneuver attitudes, or a combination of the two: in-plane (along the spacecraft velocity vector) or out-of-plane (along the spacecraft angular momentum vector). The burns are performed as fixed-attitude maneuvers and are usually scheduled on the morning of the first Wednesday of a new 2-week spacecraft background sequence. In-plane maneuvers are used for apsis height control to maintain the PSO ground track walk repeat error between $\pm$40 km; most have been performed at orbit periapsis to raise orbit apoapsis. The choice between executing at periapsis or apoapsis usually depends on two factors: the maneuver placement allows adequate tracking before and after the maneuver, and the frozen condition is adequately controlled (i.e., the spread in the $e - \omega$ space is maintained or improved). Out-of-plane maneuvers are used to control the LMST by changing the inclination. They have been implemented twice before in the PSP to drift the LMST back towards 3:00 PM at the ascending equator crossing: OTM-12 in February 2009 and OTM-39 in November 2014.

MRO's Role in Extended Mission Operations (Mars Program Office)

As an asset of the Mars Exploration Program Office, MRO continues to perform science observations but is also directed to provide telecommunication relay for surface assets and perform characterization of landing sites for future Mars landers and rovers. As previously described, MRO has provided telecommunication relay support to the Mars Phoenix lander (2008) and the Mars Science Laboratory rover (2012 – present). Though neither mission is directly part of the Mars Exploration Program Office, MRO will provide similar telecommunication support to the InSight and ExoMars/EDM missions (InSight is a competed NASA Discovery Program mission, and EDM is a European Space Agency demonstration mission). This paper details the Navigation support strategy planned for these missions.

MRO SUPPORT OF PAST MISSIONS: PHOENIX AND MSL

The primary aim of MRO supporting past missions arriving at Mars have been to provide telecommunication support during the critical EDL phase. Imaging these assets during descent remained only a secondary goal. However, MRO succeeded in doing both for Phoenix and MSL missions.

There was no request from Phoenix mission to change MRO's LMST, but only needed on-orbit phasing to a required target within ±30 seconds. MRO's final phasing offset was 0.25 seconds earlier than the phasing target requested by Phoenix. Like Phoenix support, MRO did not have to alter its LMST for MSL. This was the case due to the choice of date that MSL launched in November 2011 and the choice of Gale Crater as the landing site. For a different launch date or different landing site MRO might have been required to alter its LMST. Hence an LMST change plan had been developed but was not needed. Thus, MRO only had to phase to the requested target again to within ±30 seconds. For this, three maneuvers were planned, of which only two implemented. The final target error at MSL EDL was 9.05 seconds late, well within the phasing requirement.

MRO SUPPORT OF FUTURE MISSIONS: INSIGHT AND EDM

InSight will be launched into a ballistic, Type 1 trajectory during a 27-day launch period from March 4–30, 2016. After an approximately six-month interplanetary cruise, InSight will arrive at Mars on September 28, 2016 satisfying the main objective of placing a lander on the Mars surface followed by the deployment of two science instruments to investigate the fundamental processes of terrestrial planet formation and evolution.[6] The current target landing location for the InSight Mission, denoted as E09, is located in the Elysium Planitia region at 4.46° N, 136.04° E. The InSight EDL sequence is expected to last between six and seven minutes.

The ExoMars program will include two missions for the 2016 and 2018 launch opportunities to Mars. 1. The ESA-led 2016 mission will supply the ExoMars Trace Gas Orbiter (TGO) that will carry an Entry, Descent and Landing Demonstrator Module (EDM). NASA scientific instruments will be accommodated on TGO to support the search and localization of methane sources on Mars.[7] The current landing site target for EDM in Meridiani Planum is 1.94° S, 6.07° W (Launch Period (LP)-open), 1.98° S, 6.04° W (LP-close). The EDM EDL duration is anticipated to be six minutes. The landing sites for InSight and EDM are shown in Figure 1.

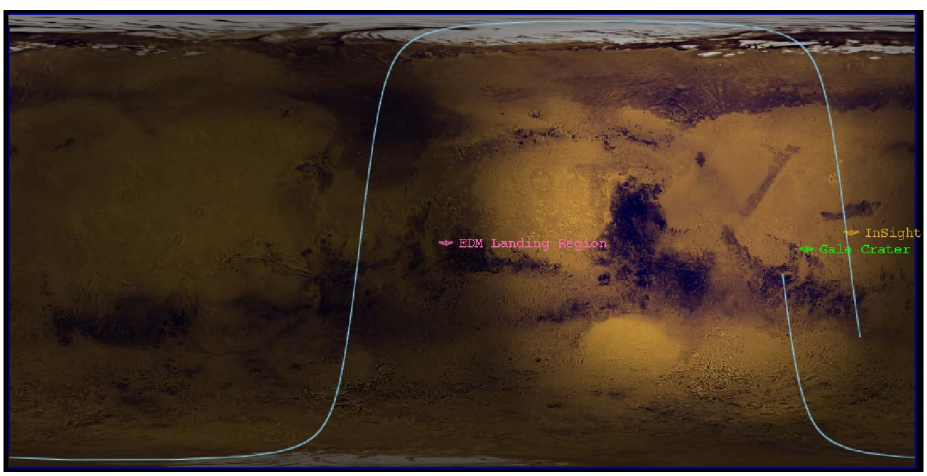


Figure 1: InSight and EDM Landing Site Geometry

Requested Support for InSight and EDM

The InSight Mission has requested MRO to move its orbit ascending node to 2:30 PM LMST at InSight EDL on September 28, 2016 and to be between −10 minutes and +30 seconds of this target LMST. Additionally, the InSight Mission has requested that MRO phases within ±30 seconds of the specified InSight entry epoch, which corresponds to within ±1.6 degrees of a requested latitude target specified at InSight entry. The LMST limits and phasing control capability are inherited from MROs support of MSL EDL phase.

For EDM support, MRO has no plan to adjust its LMST for EDM EDL or subsequent overflights. The MRO orbit LMST during EDM support is expected to be only a few minutes earlier than the targeted 2:30 PM achieved three weeks earlier to support InSight EDL. Based on orbit-phasing analysis assuming EDM EDL support, this phasing control capability was recommended by MRO Navigation to be within ±90 seconds of the specified EDM entry epoch if EDM EDL support is desired. This corresponds to within ±4.8 degrees of a requested latitude target specified at EDM entry. If ESA requests that the EDM first overflight is to be supported instead, this phasing requirement will be relaxed to ±5 min of the specified EDM overflight time. The duration of MRO's support will cover at least the first four days of the surface mission following EDM EDL. The support requirements for both InSight and EDM are summarized in Table 1.

Table 1: InSight and EDM Support Requirements

Mission	LMST Requirement (Target + Tolerance)	Phasing Control Requirement
InSight EDL	2:30:00 PM (−10 min to +30 sec)	±30 sec
EDM EDL –*OR*– EDM First Overflight	No Specified Requirement	±90 sec* ±5 min

* Phasing control capability per analysis (Navigation recommendation to ESA)

Timeline of Events

Some significant events leading to the eventual InSight EDL support period are given in Table 2. Prior to the implementation of OCM-1, the LTST had dipped to a local minimum of about 2:15 PM on April 23, 2015. There was no concern as the operating range for the spacecraft is between 2 and 4 PM. Following that was the Solar Conjunction, during which time the Doppler data that is used for orbit determination were very noisy. Hence OCM-1 was placed well after the conjunction. Also, by not changing LMST any earlier that July 29, 2015 it was possible to delay compromising efforts to collect data for science. The launch period of ESA's EDM is early 2016 while that for InSight is in March 2016. After the InSight launch, depending on the launch date, small corrections to the LMST could be applied. The phasing support strategy for both missions would be finalized during April – August 2016 time period. After InSight EDL, MRO would start relaying data from InSight from the surface. However, after EDM landing, relay support would be provided for four days only as EDM lander mission is expected to last for a short duration. A week after EDM landing (4 weeks after InSight landing) is the baseline plan to perform OCM-2 followed by OCM-3 in April, 2017. This should put MRO back to PSO well prior to the next Solar Conjunction in July 2017.

Table 2: Timeline of Events

Event	Date(s)
Minimum LTST (2:15 PM)	April 23, 2015
Solar Conjunction	June 3–25, 2015
Baseline OCM-1	July 29, 2015
EDM Launch Period	January 7–27, 2016
InSight Launch Period	March 4–30, 2016
Phasing Window	April 6–September 21, 2016
InSight EDL	September 28, 2016
Phasing Window	October 5–12 2016
EDM EDL	October 19, 2016
EDM Surface Mission	October 19–27, 2016
Baseline OCM-2	October 26, 2016
Minimum LTST (2:00 PM)	February 9, 2017
Baseline OCM-3	April 5, 2017
Solar Conjunction	July 18–August 4, 2017

BASELINE SUPPORT STRATEGY FOR INSIGHT AND EDM

LMST Change (InSight Only)

The LMST changes required for InSight EDL and return to PSO can be accomplished by performing out-of-plane maneuvers. These inclination-change maneuvers are referred to as Orbit Change Maneuvers (OCMs). MRO Navigation identified and examined three OCM strategies that achieve the desired 2:30 PM LMST at the time of InSight EDL:

- *Decreasing-LMST Strategy (Baseline Strategy)*: In this strategy, three OCMs are implemented. The first OCM is performed well in advance of the InSight landing to drift from the PSO LMST of 3:00 PM to the requested 2:30 PM LMST at InSight EDL. The MRO orbit LMST will continue to decrease following InSight EDL through EDM EDL. The second OCM is executed shortly after the InSight and EDM EDLs to increase the LMST towards 3:00 PM LMST. The third OCM is performed to stop and maintain the LMST at 3:00 PM once it has been reached. This approach would have been utilized for MSL if the LMST requirement for EDL support was earlier than 3:00 PM.[8]
- *Increasing-LMST Strategy*: This strategy also involves three OCMs, but differs from the previous strategy by placing the second OCM prior to InSight EDL. The first OCM has a faster drift rate to an earlier LMST, while the second OCM is performed to return to 3:00 PM LMST such that 2:30 PM is reached at the time of InSight EDL. The last OCM is performed to arrest the LMST at 3:00 PM like the decreasing-LMST strategy.
- *Constant-LMST Strategy*: An additional OCM is included in this strategy (total of four OCMs). The first OCM is targeted to 2:30 PM LMST well before InSight EDL and the second OCM is used to stop the LMST drift and maintain 2:30 PM LMST. The third OCM is performed after InSight EDL to return to the 3:00 PM LMST configuration in conjunction with the fourth OCM which stops the LMST drift at 3:00 PM.

The strategy of decreasing the LMST through InSight EDL was chosen by the MRO Project as the baseline strategy for InSight EDL support. This strategy does not compromise the InSight orbit phasing since the only OCM prior to InSight EDL can be performed many months earlier allowing ample time for cleanup maneuvers to be performed if needed. This strategy also keeps the overall ΔV cost low by minimizing the cost of the post-EDL OCMs (OCMs 2 and 3). One of the main concerns following the support of InSight and EDM and the return to the PSO is the possible violation of the 2:00 PM minimum LTST constraint in February 2017. To keep the LTST above 2:00 PM, OCM-2 is necessarily a large maneuver since a long drift time to an LMST of 3:00 PM would cause the minimum LTST to dip below 2:00 PM. The total required maneuver ΔV for supporting InSight EDL at 2:30 PM LMST on September 28, 2016 and returning to the MRO PSO configuration is 40.6 m/s via three OCMs using the decreasing-LMST strategy as shown in Table 3.

Table 3: Baseline OCM Strategy (20150225 Reference Trajectory)

Maneuver	Maneuver Epoch (UTC-SCET)	Maneuver Location	ΔV (m/s)	Prop. Usage (kg)	Inc. Change (deg)
OCM-1	29-JUL-2015 13:16:31	218 days before InSight Launch Period	5.4	3.0	−0.09
OCM-2	26-OCT-2016 12:51:15	InSight EDL + 28 days	20.2	11.2	+0.34
OCM-3	05-APR-2017 14:36:51	InSight EDL + 189 days	15.0	8.3	−0.25
		Total	40.6	22.5	

This total ΔV is based on the 20150225 Reference Trajectory which was released on March 3, 2015 using an initial state from the February 12, 2015 OD predict solution (orbit 40060). It replaces the 20131029 Reference Trajectory issued on November 8, 2013. The total ΔV in this reference trajectory update was less than the total given in the 20131029 Reference Trajectory by about 1.4 m/s. This decrease in the predicted ΔV can be attributed to the following changes between reference trajectories:

- Originally scheduled for December 17, 2014, OTM-39 was performed earlier on November 19, 2014 to turn the LMST drift back towards the PSO LMST (3:00 PM) via an inclination change.
- OCM-2 date was set to Wednesday, October 26, 2016 (originally assumed October 20, 2016).
- OCM-3 date was set to Wednesday, April 5, 2017 (originally assumed April 10, 2017).

Figure 2 displays the local solar time profile (LMST and LTST) from February 2015 through the end of 2017. The profile starts just prior to the minimum LTST of 2:15 PM attained in April 2015 and solar conjunction in June 2015 and goes through the EDM and InSight launches in January and March 2016, the InSight and EDM EDLs in September and October 2016, the minimum LTST of 2:00 PM in February 2017, and solar conjunction from July to August 2017. The three planned OCMs are also indicated, as well as the OCM-1 opportunities (discussed in detail in a later section) and the Phasing Strategy Decision Window (detailed in the next section).

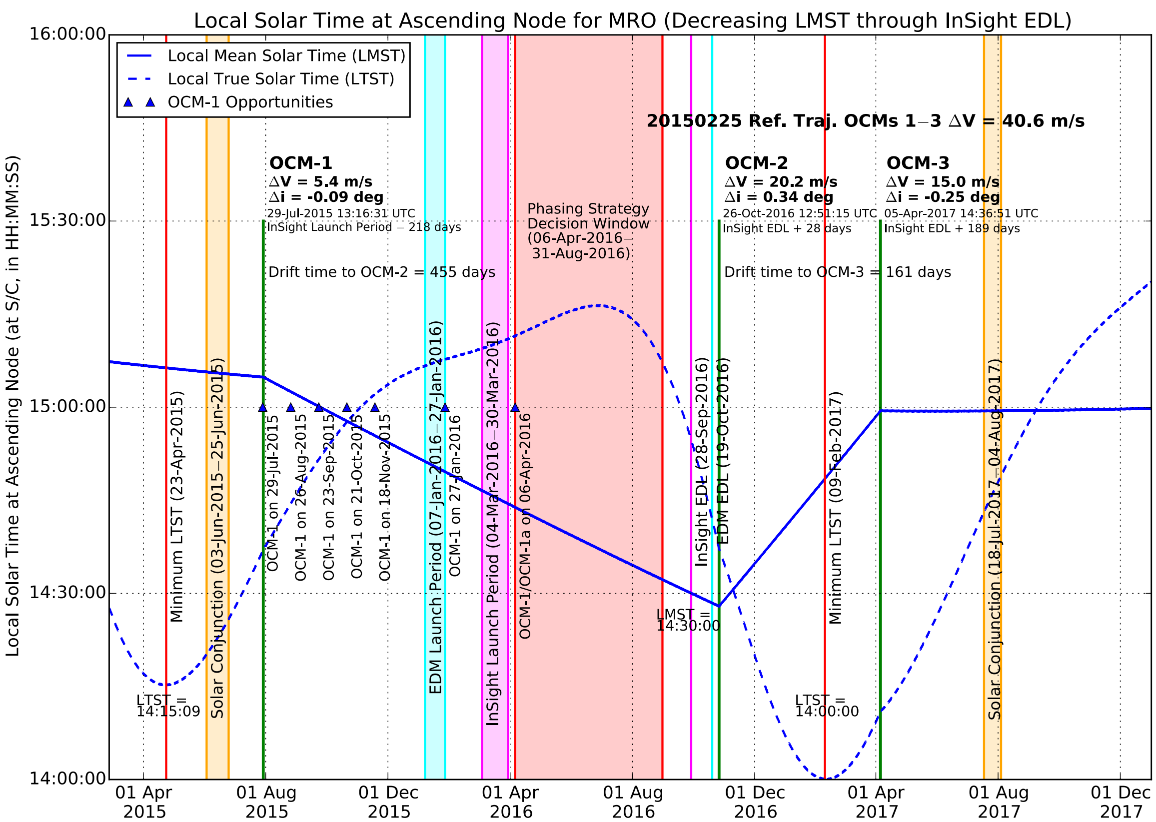


Figure 2: Local Solar Time Profile (20150225 Reference Trajectory)

Figure 3 shows the mean inclination profile from February 2015 through December 2017. All three OCMs will induce the largest changes in MRO's orbit inclination to date.

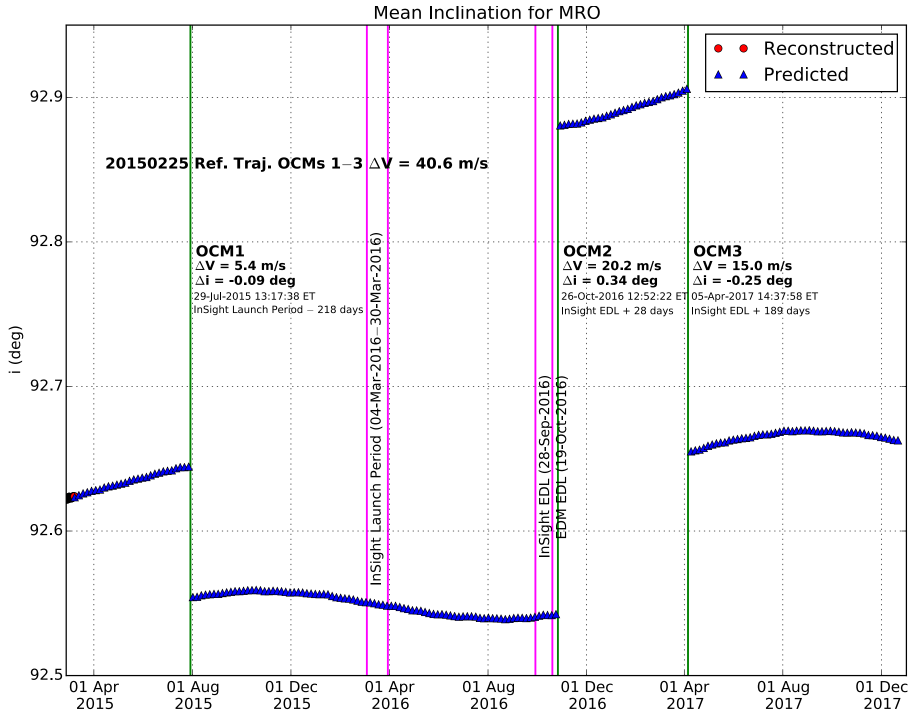


Figure 3: Mean Inclination Profile (20150225 Reference Trajectory)

Orbit Phasing Change (InSight and EDM)

Orbit phasing is accomplished through in-plane maneuvers, referred to as Orbit Synchronization Maneuvers (OSMs). These phasing control maneuvers are used to adjust the MRO orbital period that over a given duration produce a desired total MRO orbit down-track timing change. Given these phasing requirements for both InSight and EDM, MRO Navigation identified and analyzed two orbit-phasing strategies:

- *Mission-Specific Phasing (Baseline Strategy)*: This strategy involves phasing MRO before each encounter, one after another, first to the InSight target conditions using an OSM that is pre-InSight entry and next to EDM target conditions using an OSM that is pre-EDM entry (post-InSight entry).

- *Dual-Mission Phasing by Adjusting Mean Period (Alternate Strategy)*: In this strategy, two OSMs are designed together (both pre-InSight) such that MRO phases to InSight target conditions while the mean orbital period is set between the InSight and EDM targets such that a deterministic OSM is not required in between the InSight and EDM EDL events (only a small statistical correction may be necessary).

The strategy to phase to the InSight and EDM target conditions separately via the Mission-Specific Phasing Strategy was selected as the nominal plan by the MRO Project. If EDM does not require coverage at a pre-determined time (as it does for coverage of the EDL event or an overflight at a specific time after landing, for example), there is no need for a ΔV in-between to phase for EDM coverage, and EDM will naturally receive its first overflight coverage whenever MRO flies over EDM for the first time. In this case, the problem reduces to a single phasing for Insight EDL, just as the previous EDL phasings for Phoenix and MSL EDLs.

However, if EDM coverage does require a pre-determined time, the first strategy works most effectively when the timing separation between the two coverages is such that the EDM phasing requires a minimal ΔV so that its error propagation is small. However, when the two coverages are separated in time such that the EDM phasing requires a large ΔV (up to the half-orbit correction), the second strategy is preferred. The second strategy sets both the absolute phasing (with respect to the Insight) and the relative phasing (with respect to the time separation between Insight and EDM) prior to both coverages such that the mean orbit of MRO is synchronized with the phasing difference between the two coverages, thus, requiring no deterministic ΔV between the two coverages. The second strategy has been analyzed in detail in an earlier paper (see Reference 9).

Orbit phasing will not occur until after the launches of EDM and InSight, the latter being the later launch (March 2016). The decision window for choosing between the two phasing strategies is currently April – August 2016, as indicated in Figure 2. Table 4 lists the current maneuver opportunities for phasing to InSight and EDM targets.

Table 4: OSM Opportunities Prior to InSight and EDM Entries

Days Prior to InSight	Date	Days Prior to InSight	Date	Days Prior to EDM	Date
175	06-APR-2016	35	24-AUG-2016		
147	04-MAY-2016	28	31-AUG-2016		
119	01-JUN-2016	21	07-SEP-2016		
91	29-JUN-2016	14	14-SEP-2016	14	05-OCT-2016
63	27-JUL-2016	7	21-SEP-2016	7	12-OCT-2016
49	10-AUG-2016	InSight Entry	28-SEP-2016	EDM Entry	19-OCT-2016

Combining LMST and Orbit Phasing Strategies

The orbit change maneuver strategies (inclination change, for LMST, and semi-major axis change, for orbit phasing) may be performed independently. However, both strategies may be combined into a single maneuver for operational convenience, and in some cases, to reduce ΔV expenditure. This combined-strategy approach was implemented in the designs of OTM-12 on February 4, 2009 (3.2 m/s), OTM-39 on November 19, 2014 (3.45 m/s), and OTM-43 (OCM-1) on July 29, 2015 (5.33 m/s). OTM-12 and OTM-39 were inclination-change maneuvers performed at the descending equator crossing which brought the LMST back towards 3:00 PM while maintaining the GTW error within prescribed bounds. At the time of OTM-39, the GTW error had nearly reached $+240$ km in order for MRO to be positioned at a safe location from incoming particles from Comet Siding Spring at the time of maximum particle fluence.[10] Performing a maneuver exclusively to control the GTW error back to -40 km would have cost about 1 m/s, but combining the in-plane component with a 3.3 m/s out-of-plane ΔV for LMST maintenance added only 0.15 m/s to the total ΔV of 3.45 m/s. Folding GTW maintenance into the design of OTM-43 (OCM-1) was also beneficial, as discussed in a later section. In-plane maneuvers to meet InSight and EDM phasing requirements will likely cause MRO's GTW error to go beyond the ± 40 km control bounds. Given this possibility, OCM-2, the inclination-change maneuver planned after the support EDM surface operations, will also be used to return MRO's GTW error to the prescribed control bounds.

UPCOMING CHALLENGES

Anticipated Atmospheric Drag and Navigation Timing Uncertainties

Anticipated atmospheric density variations are the biggest error source to the MRO navigation accuracy, second only to a large maneuver execution error. As shown in Figure 4, the accumulated ΔV per orbit due to atmospheric drag is anticipated to be much higher in the time frame leading up to the InSight and EDM EDL events than when Phoenix and MSL mission orbit phasing was performed. This is due to the timing of mission arrival at Mars and orbit geometry (solar longitude of Mars at the time of each EDL event).

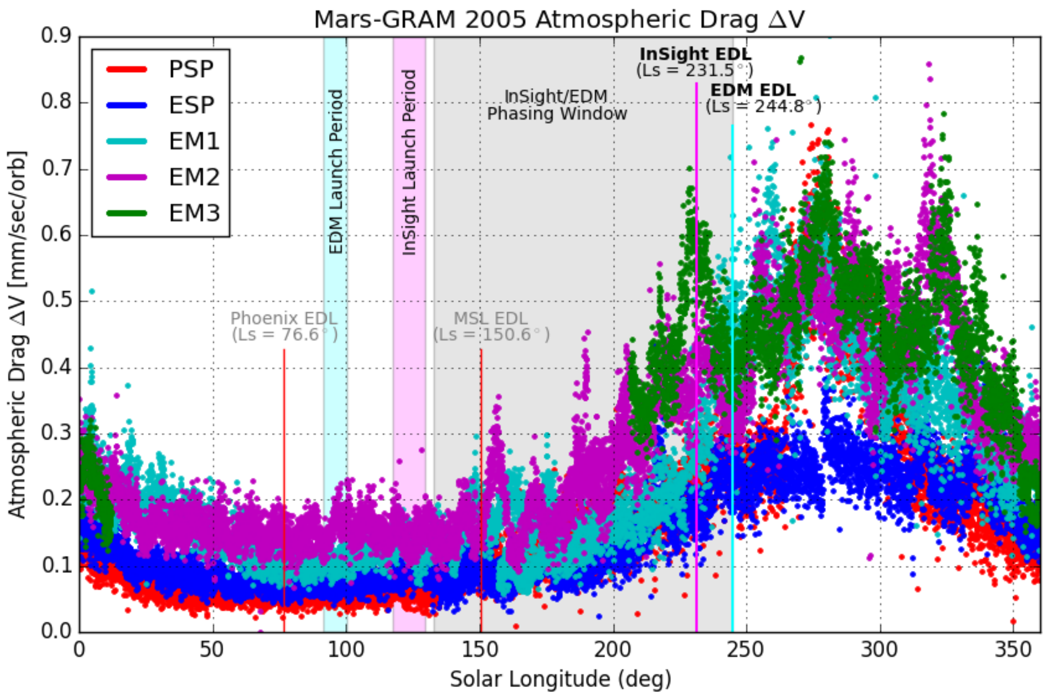


Figure 4: Atmospheric Drag ΔV Experienced by MRO Through July 2015

Phasing maneuver planning has been performed using an anticipated drag ΔV of 0.5 mm/s per orbit. The uncertainty on this ΔV can be large and is modeled using two components: a bias term (quadratic error growth) and a white-noise term (linear error growth). Consequently, the expected navigation timing uncertainties (see Figure 5) are significantly larger than those used to determine down track timing uncertainty at the time of Phoenix and MSL EDL events (as comparison, down-track timing uncertainty 30 days prior to MSL EDL was about 20 seconds; for InSight, it is modeled as approximately 70 seconds). To mitigate undesirably over-shooting the phasing target, orbit phasing error is corrected up to the navigation down-track timing uncertainty at the time of the phasing maneuver. This strategy nominally requires a phasing maneuver be performed shortly before the EDL event. Per the anticipated down-track timing uncertainty, the final InSight phasing maneuver will need to be placed closer to the InSight EDL event to guarantee the same MRO orbit timing uncertainty as provided to MSL. Currently, MRO Navigation recommends the final OSMs to the InSight and EDM phasing targets are performed within two weeks of the targets, with each OD data cutoff (DCO) at four days earlier.

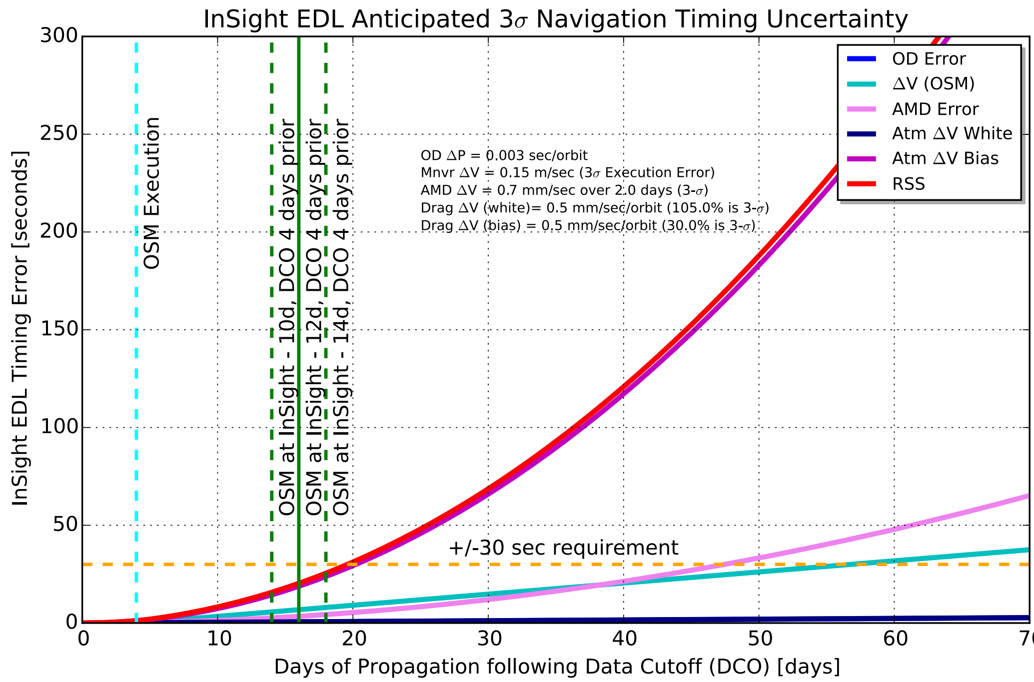
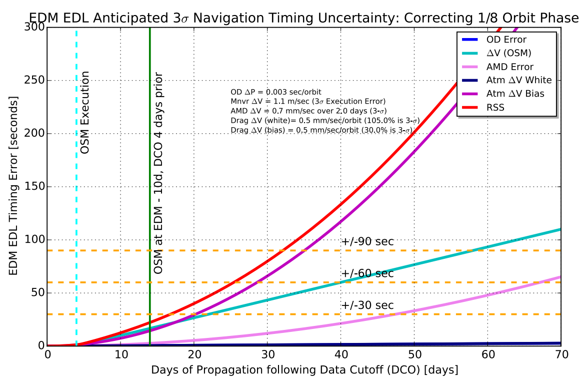
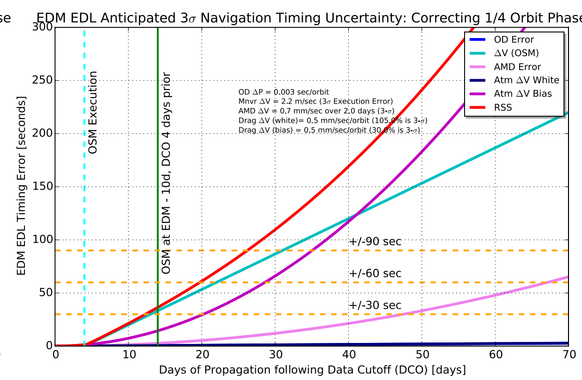


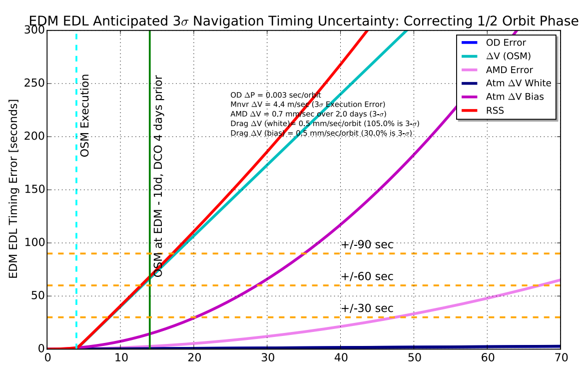
Figure 5: MRO Navigation Timing Uncertainty (3-σ) Prior to InSight EDL



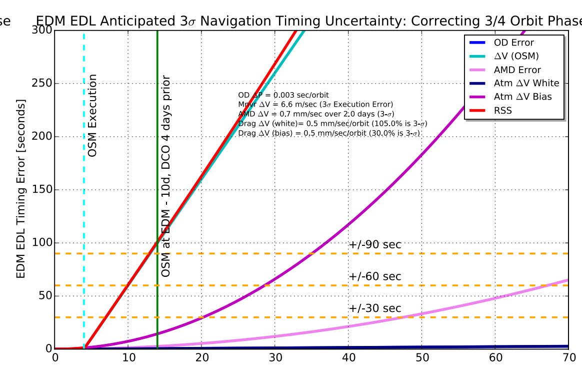
(a) Correcting 1/8 Orbit Phase Error (1.1 m/s OSM)



(b) Correcting 1/4 Orbit Phase Error (2.2 m/s OSM)



(c) Correcting 1/2 Orbit Phase Error (4.4 m/s OSM)



(d) Correcting 3/4 Orbit Phase Error (6.6 m/s OSM)

Figure 6: MRO Navigation Timing Uncertainty (3-σ) Scenarios Prior to EDM EDL

Determining EDM EDL Phasing Control Capability

Analysis conducted by MRO Navigation demonstrated that the ± 30 sec InSight EDL phasing accuracy requirement can be met with a small OSM (e.g., 0.15 m/s) performed 14 days prior to InSight EDL. With only three weeks between the InSight and EDM EDL events, the earliest an OSM can be executed for the EDM phasing target, whether it is EDM EDL or the first overflight, is 14 days prior. Any earlier than 14 days would conflict with the required seven days of post-InSight landing overflight support by MRO. With this constraint and assuming an EDM EDL target, MRO Navigation examined several orbit phasing correction scenarios to meet an EDM phasing target. Figure 6 presents the 1/8, 1/4, 1/2, and 3/4 phasing error cases, requiring corrections with 1.1 m/s, 2.2 m/s, 4.4 m/s, and 6.6 m/s OSMs, respectively. The half-orbit phase error case, as seen in Figure 6c, represents the worst case scenario; the three-quarter phase error case is only feasible if the in-plane maneuver is limited to one direction (as shown in Figure 6d). Execution errors from an OSM of 4.4 m/s performed 10 days prior to EDM EDL and anticipated 0.5 mm/s/orbit atmospheric drag ΔVs led to the recommendation of +/-90 sec as the EDM EDL phasing accuracy capability.

OCM-1 Execution Time

As of July 2015, MRO has about 230 kg of remaining useable propellant. Approximately 15 kg per year is used to perform orbit maintenance (OTMs) and momentum wheel desaturation events. The propellant required to change MRO's node from 3:00 PM to 2:30 PM significantly decreases MRO's on-orbit lifetime. It is extremely desirable to minimize the propellant (ΔV) required for node change maneuvers. As soon as an out-of-plane (inclination change) maneuver is performed, the MRO orbit is no longer sun-synchronous and will drift away from the nominal 3:00 PM LMST configuration. This induced drift rate, and subsequent nulling/reversing of the induced drift rate, is used to achieve the desired local solar time (LMST) at a desired future date. A fast-drift scenario achieves the desired node quicker, but requires more fuel to induce a higher drift rate; a slow-drift scenario achieves the desired node slowly, but provides significant propellant savings over a fast-drift scenario. However, implementing the slow-drift scenario is not without cost, as the spacecraft may be required to spend additional fuel to accommodate late pre-launch mission scenario changes. As the maximum InSight cruise duration (launch period open to landing date) is only 208 days, waiting until post-launch to perform an inclination change maneuver is prohibitively expensive. Therefore, the MRO project balanced the propellant savings of a slow-drift scenario with the risk (cost) of needing to adapt to Insight mission changes. The propellant savings outweighed the risk of mission changes, and the first OCM is scheduled for July 29, 2015 (218 days prior to InSight launch period open). Table 5 presents the total ΔV cost of OCMs 1, 2, and 3 with the baseline OCM-1 (July 29, 2015) through a 36-week delay of OCM-1 (April 6, 2016).

Table 5: OCM-1 Scenarios

Strategy	OCM-1		OCM-2 on 10/26/2016	OCM-3 on 4/5/2017		OCMs 1+2+3	
	Date	ΔV (m/s)	ΔV (m/s)	ΔV (m/s)	LMST (PM)	ΔV (m/s)	ΔV − #1 (m/s)
#1: Baseline OCMs (20150225 Ref. Traj.)	7/29/2015	5.40	20.20	15.00	2:59:23	40.60	–
#2: OCM-1 Delayed 4 Weeks	8/26/2015	5.80	20.80	15.15	2:59:27	41.75	1.15
#3: OCM-1 Delayed 8 Weeks	9/23/2015	6.22	21.25	15.25	2:59:31	42.72	2.12
#4: OCM-1 Delayed 12 Weeks	10/21/2015	6.70	21.90	15.40	2:59:46	44.00	3.40
#5: OCM-1 Delayed 16 Weeks	11/18/2015	7.30	22.60	15.60	2:59:44	45.50	4.90
#6: OCM-1 Delayed 26 Weeks	1/27/2016	9.45	25.55	16.30	3:00:17	51.30	10.70
#7: OCM-1 Delayed 36 Weeks	4/6/2016	13.20	30.35	17.20	3:00:59	60.75	20.15

The April 6, 2016 OCM-1 scenario is the first post-InSight launch maneuver opportunity, representing the smallest ΔV cost incurred by waiting to change the LMST drift until InSight has launched (more than 20 m/s penalty). The total cost of the OCMs as OCM-1 is delayed is exponential, as illustrated in Figure 7.

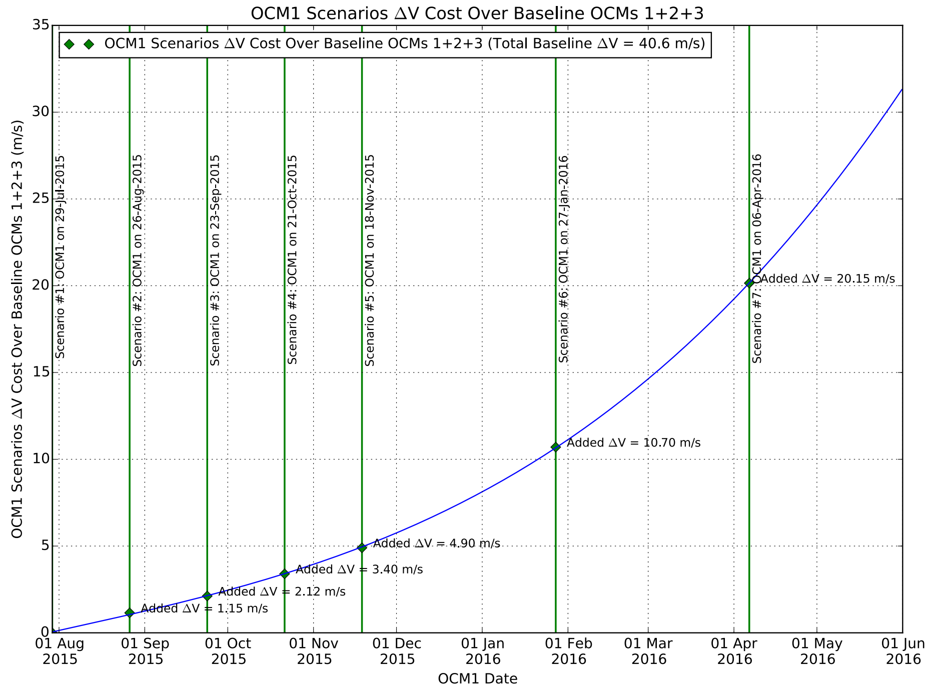


Figure 7: OCM-1 Scenarios Cost

LTST Mission Constraint

Due to spacecraft thermal operating constraints, the Local True Solar Time (LTST) of the MRO orbit is to be maintained between 2:00 and 4:00 PM (ascending equator). The relation of local mean solar time (LMST) and local true solar time (LTST) is governed by the Equation of Time (see Reference 11). LTST will vary by nearly 45 minutes over the course of a Mars year due to the eccentricity of the Mars orbit around the Sun, as shown in the history of local solar time in Figure 8. In early 2009 the LTST reached its highest value of about 3:50 PM and in mid 2011 it attained the lowest LTST to date of approximately 2:07 PM. As illustrated in Figure 2, after InSight and EDM EDLs the local true solar time approaches 2:00 PM LTST (the orbit LTST would trend downward even if the MRO PSO remained at 3:00 PM LMST). The MRO orbit LTST will drop below 2:00 PM unless an inclination-change maneuver (to reverse the nodal drift rate and trend back towards 3:00 PM LMST) is not performed shortly following EDM EDL. In other words, depending on the location of OCM-1, OCM-2 must be performed on a given future date. For the baseline OCM-1 performed on July 29, 2015, OCM-2 must be performed by October 26, 2016 (InSight EDL + 28 days, or EDM EDL + 7 days). Per the OCM strategies investigated, both the increasing-LMST strategy and the constant-LMST strategy would potentially mitigate this risk. However, these strategies were unfavorable because they both generally require a large inclination-change maneuver to be performed close to the InSight EDL event, of which the anticipate execution errors could be large. To fully preserve orbit phasing capability, the OCM-2 maneuver is planned to be executed following both EDL events.

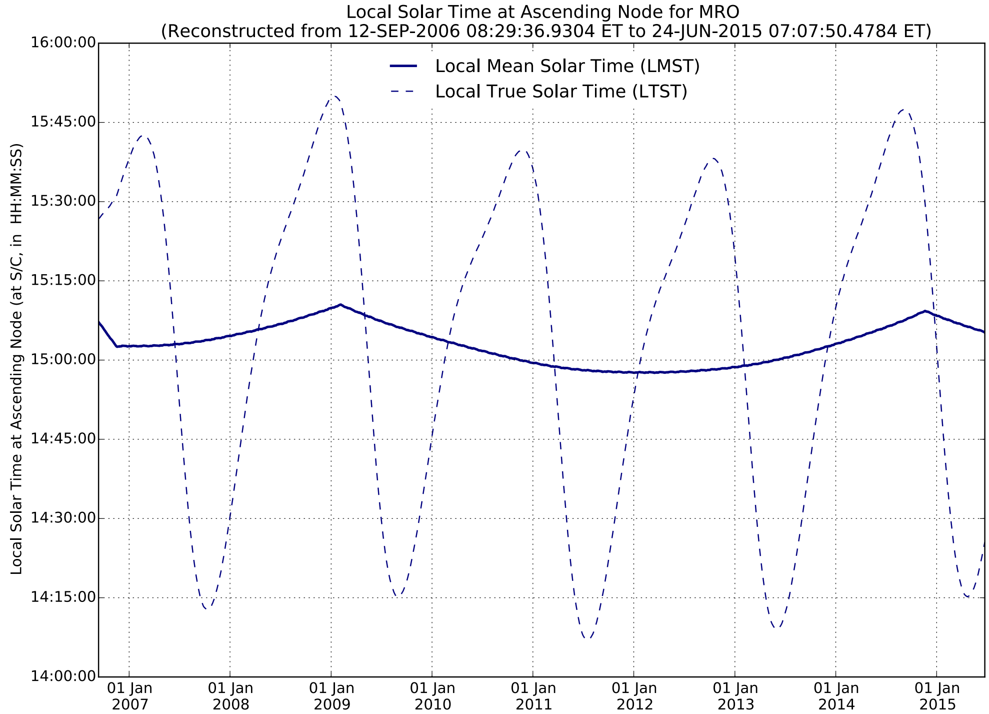


Figure 8: History of Local Solar Time at Ascending Node

Impact of Maneuver Execution Performance

A Gates model[12] is used to model execution errors for propulsive maneuvers. The magnitude components (fixed magnitude and proportional magnitude) of the Gates model contribute to down-track timing error. For small maneuvers (as anticipated for the final phasing maneuver corrections), the fixed-magnitude error is 5 mm/sec and the proportional-magnitude error is 2% (3σ). Down-track timing is primarily impacted by magnitude error. Maneuver execution errors encountered during MRO Operations are typically less than 1% of the desired maneuver magnitude, more frequently on the overburn side, as seen in Figure 9 in Appendix: Maneuver Performance.

For OCM-1 Scenarios #1 –7 given in Table 5, a 3σ execution error in magnitude (about a 2% proportional-magnitude error) will result in an LMST error range at InSight EDL of $\pm$27 sec to $\pm$47 sec (e.g., 47 sec early for overburns, 47 sec late for underburns). A one degree pointing error can contribute an additional 22 sec to the LMST error range (hence, $\pm$16 sec to $\pm$58 sec). For example, a 3σ OCM-1 underburn can undershoot the 2:30 PM LMST at InSight EDL by 58 sec (2:30:58 PM), violating the LMST requirement. However, several cleanup maneuver opportunities exist from August 2014 to April 2015 to correct the LMST at InSight EDL, which can also be combined with GTW maintenance maneuvers. For OCM-2 Delay Scenarios (see Table 8 in the next section), a 3σ execution error in magnitude will yield an LTST error range of $\pm$28 sec to $\pm$34 sec (e.g., 34 sec late for overburns, 34 sec early for underburns). A one degree pointing error can increase the LTST error range by more than 20 sec (hence, $\pm$18 sec to $\pm$42 sec). For example, a 3σ OCM-2 underburn can lower the minimum LTST in the January/February 2017 timeframe by 42 sec (1:59:18 PM). If the minimum LTST of 2 PM is hard limit, a cleanup maneuver can be performed to increase the minimum LTST within a month of OCM-2 if necessary. OCM-3 execution errors are not as much a concern since long drift times to 3 PM LMST do not require immediate action and future OTMs can be used to correct the inclination if needed.

Impact of Orbit Phasing and LMST Change on PSO

The MRO orbit ground track is permitted to drift during the orbit phasing interval, and may deviate by tens to hundreds of kilometers from the nominal repeat pattern. Large deviations were observed for Phoenix phasing support (about -90 km), MSL phasing support (approximately $+60$ km), as well as orbit phasing performed for Comet Siding Spring risk mitigation (nearly $+240$ km).[10] The change in LMST from the operating range of 3:00 PM $\pm$ 15 minutes impacts MRO's temperature profile and target lighting conditions. These impacts, however, are acceptable by Science for the duration of the support of the InSight and EDM missions.

OCM CONTINGENCY/DELAY SCENARIOS

Nominal OCM-1 and Return to PSO Scenarios

In the event the baseline OCM-1 on July 29, 2015 is performed and the InSight launch is delayed or cancelled, a quick return to the PSO configuration will be desired by the MRO Project. Several OCM-2 opportunities for returning to PSO are shown in Table 6. In the first case, OCM-3 is not required since OCM-2 will be used to stop the LMST at 3:00 PM.

Table 6: Nominal OCM-1 and Return to PSO Scenarios

Description	OCM-2		OCM-3 on 4/5/2017		OCMs 1+2+3
OCM-1 on 7/29/2015	Date	ΔV (m/s)	ΔV (m/s)	LMST (PM)	ΔV (m/s)
#1: Start Return to PSO After 8 Weeks	9/23/2015	6.00	–	3:00:51	11.40
#2: Start Return to PSO After 16 Weeks	11/18/2015	6.50	1.30	2:59:49	13.20
#3: Start Return to PSO After 26 Weeks	1/27/2016	7.60	2.50	3:00:05	15.50

Post-InSight Launch OCM Scenarios

On May 27, 2015, the Navigation Advisory Group (NAG) Review Board of the Mission Design and Navigation Section at JPL had recommended adjusting the InSight EDL LMST target to an earlier 2:29:30 PM (Scenario #2 in Table 7) to the MRO Project. However, upon further analysis by the InSight Mission Navigation Team, it was determined that an LMST of 2:23 PM would provide more robustness in the EDL visibility for all planned InSight launch dates (March 4–30, 2016 launch period). If InSight launches in the final five days of its launch period, MRO will perform an additional maneuver (OCM-1a) to attain the needed LMST (Scenario #4 in Table 7). The introduction of OCM-1a following the InSight launch period can also be used to correct the LMST at InSight EDL, eliminating the need for an LMST bias recommended by the NAG review board.

Table 7: OCM-1 and OCM-1a Targeting Scenarios

Description	OCM-1	OCM-1a	OCM-2	OCM-3	OCMs 1+1a+2+3	
OCM-1 on 7/29/2015, OCM-1a on 4/6/2016, OCM-2 on 10/26/2016, OCM-3 on 4/5/2017	ΔV (m/s)	ΔV (m/s)	ΔV (m/s)	ΔV (m/s)	ΔV (m/s)	ΔV − #1 (m/s)
#1: Nominal OCM-1 (Target 2:30 PM LMST)	5.40	–	20.20	15.00	40.60	–
#2: Bias OCM-1 to 2:29:30 PM LMST	5.50	–	20.80	15.50	41.80	1.20
#3: Target OCM-1 to 2:23 PM LMST	6.63	–	27.00	20.50	54.13	13.53
#4: Nominal OCM-1, Target OCM-1a to 2:23 PM LMST	5.40	3.00	29.33	21.00	58.73	18.13

OCM-2 Delay Scenarios

Table 8 shows the effect of delaying OCM-2 by up to four weeks. An OCM-2 delay not only increases the size of the maneuver, but also increases the size of OCM-3. The large ΔV penalty is due to the need to constrain the LTST above the 2:00 PM minimum requirement.

Table 8: OCM-2 Delay Scenarios

Description	OCM-2		OCM-3			OCMs 1+2+3	
OCM-1 on 7/29/2015	Date	ΔV (m/s)	Date	ΔV (m/s)	LMST (PM)	ΔV (m/s)	ΔV− #1 (m/s)
#1: Baseline OCM-2 (20150225 Ref. Traj.)	10/26/2016	20.20	4/5/2017	15.00	2:59:23	40.60	–
#2: Delay OCM-2 by 1 Week	11/2/2016	21.63	4/5/2017	16.50	3:00:26	43.53	2.93
#3: Delay OCM-2 by 2 Weeks	11/9/2016	23.35	3/29/2017	18.00	3:00:02	46.75	6.15
#4: Delay OCM-2 by 3 Weeks	11/16/2016	25.45	3/22/2017	20.00	2:59:41	50.85	10.25
#5: Delay OCM-2 by 4 Weeks	11/23/2016	28.05	3/15/2017	22.50	2:59:21	55.95	15.35

OCM-3 Delay Scenarios

The impact of delaying OCM-3 is not as severe as delaying OCM-2. This is primarily due to the flexibility in achieving the PSO LMST within ±15 minutes. For all of the cases shown in Table 9, a 15 m/s OCM-3 will stop the drift at the current LMST. As shown in Scenario #3, If OCM-3 is delayed by 10 weeks when the LMST is well beyond 3:00 PM but still within the PSO tolerances, a long nodal drift back to 3:00 PM can be implemented at a minimal cost of about 2 m/s.

Table 9: OCM-3 Delay Scenarios

Description	OCM-3					OCMs 1+2+3	
OCM-1 on 7/29/2015, OCM-2 on 10/26/2016	Date	ΔV (m/s)	LMST at OCM-3	Date of Achieved LMST	Achieved LMST (PM)	ΔV (m/s)	ΔV− #1 (m/s)
#1: Baseline OCM-3 (20150225 Ref. Traj.)	4/5/2017	15.00	14:59:23	4/5/2017	2:59:23	40.60	–
#2: Delay OCM-3 by 4 Weeks	5/3/2017	16.05	3:04:54	11/25/2018	3:00:06	41.65	1.05
#3: Delay OCM-3 by 10 Weeks	6/14/2017	16.95	3:13:15	Early 2020	3:00:00	42.55	1.95

CONCLUSION

The MRO Navigation Team has a robust plan to support the InSight Mission's EDL on Mars as well as the ExoMars EDM Mission. Various scenarios for performing the OCMs were extensively investigated, including plans to adjust the LMST depending on the actual launch date of the InSight Mission. The initial step towards achieving 2:30 PM LMST at the time of InSight EDL has already been taken by the recent performance of OCM-1 on July 29, 2015. The details of the OCMs and OSMs utilized for these supports will be covered in future publications. The phasing maneuvers to support InSight EDL will commence next spring. More phasing will be done as needed to support either EDM EDL or its first overflight. Following the landings, MRO plans to provide relay support during surface operations of these landers (as well as support the currently operating Opportunity and Curiosity rovers) and return to MRO science operations at the earliest opportunity.

APPENDIX: MANEUVER PERFORMANCE

The maneuver performance during MRO's science operations are shown in the Figure 8. The Y-axis shows the percentage of difference in ΔV magnitude. Most of the maneuvers performed well within $\pm 2\%$. Also highlighted with blue circles are the three inclination change maneuvers (OTM-12, OTM-39, and OTM-43). Most of the recent maneuvers have had slight over-performances.

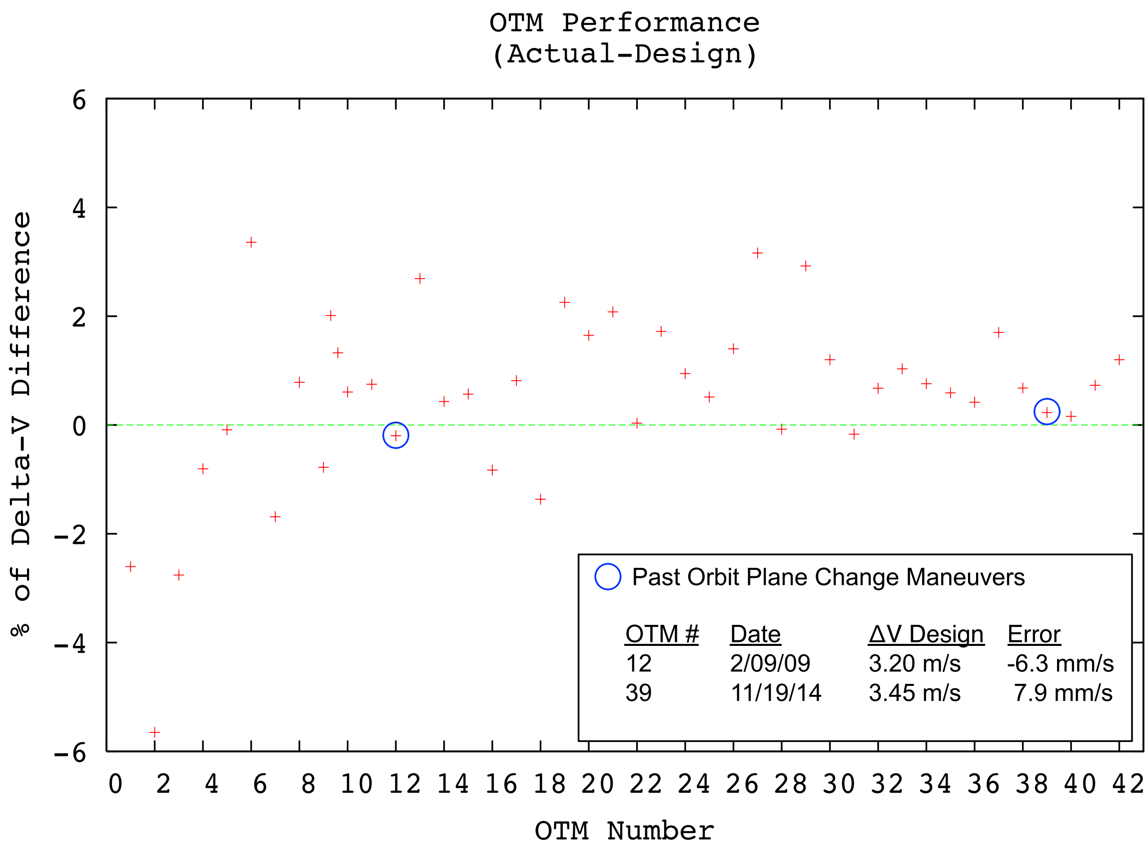


Figure 9: Performance of OTMs 1–43 (February 2007 – July 2015)

ACKNOWLEDGMENTS

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The authors wish to thank Fernando Abilleira, Allen Halsell, Jennie Johanneson, and Dan Johnston for reviewing this paper.

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