

# Mars Reconnaissance Orbiter Navigation Strategy for Mars Science Laboratory Entry, Descent and Landing Telecommunication Relay Support

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The Mars Reconnaissance Orbiter (MRO) is an orbiting asset that performs remote sensing observations in order to characterize the surface, subsurface and atmosphere of Mars. To support upcoming NASA Mars Exploration Program Office objectives, MRO will be used as a relay communication link for the Mars Science Laboratory (MSL) mission during the MSL Entry, Descent and Landing sequence. To do so, MRO Navigation must synchronize the MRO Primary Science Orbit (PSO) with a set of target conditions requested by the MSL Navigation Team; this may be accomplished via propulsive maneuvers. This paper describes the MRO Navigation strategy for and operational performance of MSL EDL relay telecommunication support.

## Nomenclature

<i>MRO</i>	Mars Reconnaissance Orbiter	<i>MOA</i>	Memorandum of Agreement
<i>MSL</i>	Mars Science Laboratory	<i>DCO</i>	Data Cut-Off
<i>EDL</i>	Entry, Descent and Landing	$R_p$	Radius of Mars
<i>ERTF</i>	EDL Relay Targets File	$\mu$	Mars gravitational parameter
<i>PSO</i>	Primary Science Orbit	$a$	orbit semimajor axis
<i>PSP</i>	Primary Science Phase	$e$	orbit eccentricity
<i>ESP</i>	Extended Science Phase	$i$	orbit inclination
<i>EM</i>	Extended Mission	$n$	orbit mean motion
<i>ACS</i>	Attitude Control System	$r$	orbit radius
<i>OTM</i>	Orbit Trim Maneuver	$\xi$	orbit energy
<i>OSM</i>	Orbit Synchronization Maneuver	$v$	orbit velocity
<i>OCM</i>	Orbit Change Maneuver	$P$	orbit period
<i>GTW</i>	Ground Track Walk	$\Delta P$	orbit period change
<i>LMST</i>	Local Mean Solar Time	$\Delta V$	orbit velocity change
<i>OIA</i>	Operational Interface Agreement		

## I. Introduction

### A. MRO Mission

The Mars Reconnaissance Orbiter spacecraft launched in August 2005 from the Space Launch Complex 41 at Cape Canaveral Air Force Station and arrived at Mars in March 2006. After a period of aerobraking, MRO began the Primary Science Phase (PSP) in November 2006 and has performed science observations at Mars ever since. Following the completion of the Prime Mission in 2008, MRO has continued to perform scientific observations in the Extended Science Phase (ESP) and Extended Mission (EM). The MRO Navigation team successfully delivered the MRO spacecraft to Mars: from Launch, to Interplanetary Cruise, to Mars Orbit

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Insertion, and finally to Science Orbit Acquisition and Primary Science Operations.<sup>1</sup> MRO Navigation continues to perform orbit determination of the MRO trajectory and maintains the Primary Science Orbit (PSO) via propulsive maintenance maneuvers.

## B. MRO Spacecraft

MRO hosts a suite of scientific instruments that can perform detailed observations and measurements in pursuit of the Mars Exploration Program's search for water on Mars. The MRO spacecraft bus, built by Lockheed Martin, provides a stable platform for conducting scientific operations and returning the observation data to Earth.

The MRO spacecraft consists of two major components: the spacecraft bus and the payload suite. The MRO spacecraft has a 3-axis stabilized Attitude Control System (ACS) that utilizes momentum wheels to provide spacecraft stability and control for targeted science observations. The spacecraft telecommunications architecture, including the large 3-meter diameter high-gain dish antenna, permits large volumes of data to be returned to Earth. The spacecraft propulsion system uses monopropellant hydrazine to perform propulsive maneuvers in order to maneuver the spacecraft. Separate sets of thrusters are used to desaturate the reaction wheels which maintain the spacecraft's attitude control.

The instrument payloads are used to perform remote sensing observations in order to characterize the surface, subsurface, and atmosphere of Mars. One instrument, the HiRise (High Resolution Imaging Science Experiment) camera, can provide the most detailed imagery of the surface of Mars of any orbiting asset (past or present). An engineering payload, the Electra Proximity Link Payload, is carried for UHF communication relay capability.<sup>4</sup> During the Primary and Extended missions, the nominal MRO configuration for non-interactive observations is such that the science instruments, which are mounted on the +Z axis face (Nadir deck), are nadir pointed (ie, areodetic or local normal to the reference ellipsoid). MRO may also perform off-nadir rolls for interactive (targeted) observations. Frequent updates of the onboard ephemeris help the spacecraft minimize interactive observation pointing errors. MRO also has the ability to point in any inertial direction for short periods of time for single events.

## C. 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.<sup>5,7</sup> The MRO PSO is defined by three key characteristics:

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

## D. Mars Exploration Program

The Mars Reconnaissance Orbiter is one asset utilized by the NASA Mars Exploration Program in the pursuit of understanding the role of water on Mars and its implications for possible past or current biological activity.<sup>10</sup> Other assets, who perform various types of scientific observations for these or for other objectives, include past orbiter (Mars Global Surveyor, 2001 Mars Odyssey) and lander (Mars Exploration Rovers, Phoenix) missions, as well as future missions (Mars Science Laboratory). These assets explore independently of one another, but can also work with and for one another as needed. The MRO spacecraft is equipped to provide critical telecommunication and imaging support to other missions at Mars. MRO, via the Electra transceiver, is capable of providing relay telecommunications with other spacecraft via store-and-forward downlink to the Deep Space Network (DSN). The MRO instrument payloads (particularly HiRise) can also be used to characterize regions identified as candidate landing sites for future Mars missions.

### 1. Past Relay Support

MRO has provided critical relay telecommunication and imaging support to other Mars Program assets. Programmatic support by MRO is two-fold: MRO provides identification, characterization, and certification of landing sites for landed assets, and provides UHF relay communication during critical mission events and during nominal operation of such landed assets.<sup>10</sup> Past programmatic support has been provided to the Mars Phoenix mission<sup>3,6</sup> and to the Mars Exploration Rovers. The Phoenix Lander, a Mars Scout mission, arrived at Mars on May 25, 2008. Having no direct-to-Earth communication link during its Entry, Descent and Landing (EDL) sequence, Phoenix relied on UHF communication (via high-fidelity open-loop recording of the UHF signal) with MRO (and also with Mars Odyssey) to relay critical EDL telemetry back to Earth. In order to view the Phoenix EDL event, MRO adjusted the PSO to phase (synchronize down-track event timing) with a set of requested orbit conditions at the time of Phoenix Entry. MRO successfully phased to the requested conditions at the time of Phoenix entry. The synchronized event also permitted MRO to record an image of Phoenix with the HiRise camera while on parachute during descent. In addition, MRO has supported relay communication (data return to Earth) for MER via 1-2× weekly relay passes. MRO has also performed additional demonstration relay passes with the MER in order to verify Electra performance.

### 2. Future Relay Support

The Mars Science Laboratory Mission launch period was from November 25, 2011 through December 18, 2011. MRO will support the Mars Science Laboratory mission in many ways. Well before launch, MRO performed an extensive imaging and characterization campaign of candidate MSL landing sites, which aided in the final selection of the Gale Crater landing site. At the time of MSL landing, MRO will perform telecommunication (primary) and imaging (secondary) support of MSL at EDL as it descends through the Mars atmosphere. Post-landing, MRO will serve as the primary telecommunication relay link between the rover and the Earth.

## II. MSL Support Requirements

The MRO trajectory requirements at the time of MSL Entry are described in an Operational Interface Agreement (OIA) between the MSL Navigation and MRO Navigation teams. A Relay Service Provider Memorandum of Agreement (MOA) outlines required MRO support as agreed to by the two projects. The orbit requirements placed on MRO Navigation are:

- Local Mean Solar Time (LMST) at the orbit Ascending Node is to be no earlier than the specified target minus 10 minutes and no later than the specified target plus 30 seconds.
- Phasing control capability is to be within  $\pm 30$  seconds of the specified MSL Entry epoch. This may also be expressed as within  $\pm 1.6$  degrees of a requested latitude target specified at MSL Entry.

If the requested target conditions cannot be naturally met by the PSO configuration, MRO Navigation will design propulsive maneuvers to achieve them. Pre-MSL launch, a propulsive maneuver strategy was developed to satisfy these requirements. The MRO Navigation strategy for and operational performance of supporting MSL Entry, Descent and Landing relay telecommunication and imaging support is discussed in this paper.

## III. MRO Navigation Support Strategy

### A. How to Meet the LMST Requirement

The Local Mean Solar Time requirement can be accomplished via an inclination change maneuver that is designed to trend the MRO orbit Local Mean Solar Time towards that desired at the time of MSL EDL. An inclination change maneuver is hereby referred to as Orbit Change Maneuver (OCM). An initial inclination change maneuver (OCM1) will remove the orbit sun-synchronous condition and trend the orbit Local Mean Solar Time toward the MSL-requested LMST. The LMST drift rate, and thus the inclination change, would be chosen such that the requested LMST is accomplished at the time of MSL Entry. Following MSL EDL, an inclination change maneuver will be used to trend the LMST back towards the nominal PSO configuration

(OCM2). A third inclination change maneuver will be used to re-establish the sun-synchronous conditions (OCM3). Longer drift times between OCMs reduces the propellant required for the orbit plane change (an expensive maneuver, from a  $\Delta V$  perspective). The OCM strategy is summarized in Table 1.

Table 1: MRO Orbit Change Maneuver (Inclination Change) Strategy.

<b>Maneuver</b>	<b>Purpose</b>	<b>Relative Placement</b>
OCM1	Trend LMST to MSL-requested condition	Post-MSL Launch
OCM2	Trend LMST to PSO configuration	Post-MSL EDL
OCM3	Re-establish sun-synchronous condition	Post-OCM2

The MOA, written well prior to MSL launch, requested that the MRO ascending node may be moved to a node earlier than the nominal PSO configuration. MSL initially considered both Type 2 (greater than 180° transfer to Mars, trajectories which required a much earlier MRO LMST) and Type 1 (less than 180° transfer to Mars, trajectories which might require an earlier MRO LMST) but ultimately decided on a Type 1 transfer. Pre-launch telecommunication analysis of the MRO PSO and the MSL cruise trajectory showed that the nominal MRO PSO LMST was found to be acceptable for telecommunication performance at the time of MSL EDL. Post-launch, the predicted MRO trajectory LMST at MSL Entry met the requested ERTF targets to within the allowed tolerance and no (expensive  $\Delta V$ ) OCM maneuvers were required.

## B. How to Meet the Phasing Requirement

The orbit phasing requirement can be accomplished via a set of period control maneuvers that are designed to alter orbit event timing such that the specified orbit latitude is achieved at the requested epoch. A period change maneuver, or phasing maneuver, is referred to as Orbit Synchronization Maneuver (OSM). An initial phasing maneuver (OSM1) will remove a majority of the phasing error. It should ideally be performed well in advance of the MSL entry epoch in order to minimize fuel consumption. A second phasing maneuver (OSM2) will be used to correct most of the remaining phasing error. A final OSM will be performed only a few days or weeks prior to the MSL Entry event in order to target the requested phasing conditions exactly (OSM3). A contingency OSM is also reserved in the event of a spacecraft anomaly (OSMC). Given that MRO operates in a low-altitude orbit at Mars, the down-track timing uncertainty of the MRO trajectory (to be discussed) is large when projected over a long propagation interval. MRO Navigation anticipated that orbit phasing maneuvers will be required for MSL support. The placement of the orbit phasing maneuvers (relative to the MSL event) is highly dependent on the anticipated MRO Navigation timing error sources. The OSM strategy is summarized in Table 2.

Table 2: MRO Orbit Synchronization Maneuver (Period Change) Strategy.

<b>Maneuver</b>	<b>Purpose</b>	<b>Relative Placement</b>
OSM1	Remove a large initial phasing bias	Post-MSL Launch
OSM2	Remove most of the remaining phasing bias	As needed
OSM3	Target to the requested phasing conditions	Prior to MSL EDL
OSMC	Contingency phasing maneuver	Post-OSM3

The MOA, written well prior to MSL launch, placed accuracy figures on the requested phasing targets. Prior to Entry-120 days, the accuracy of the requested targets was  $\pm 10$  minutes; from Entry-120 days to Entry-56 days, the accuracy of the requested targets was  $\pm 2$  minutes; from Entry-56 days to Entry, the targets requested were to be achieved within the required phasing tolerance ( $\pm 30$  seconds). MRO Navigation kept these phasing accuracy figures in mind when designing the orbit phasing strategy.

## IV. Propulsive Maneuver Design and Placement

Since the start of the PSP, MRO Navigation has maintained the PSO via propulsive maneuvers, or Orbit Trim Maneuvers (OTMs). Orbit Trim Maneuvers for MSL support are nominally placed on the first Wednesday of a new 2-week spacecraft background sequence at between 14:00 and 15:00 UTC. For nominal orbit maintenance, OTMs are performed no more frequently than every 28 days. Propulsive maneuvers implemented by the MRO spacecraft are designed in a spacecraft-centered RTN (radial-transverse-normal) coordinate frame. MRO implements a desired  $\Delta V$  in one of two standard (nominal) attitude configurations, or a combination of the two:

- **In-plane maintenance maneuver:**  $\Delta V$  is applied along the spacecraft velocity vector (transverse direction) to raise or lower the orbit semimajor axis via raising or lowering an orbit apsis. This type of maneuver is used to control the orbit GTW (and also the orbit frozen condition).
- **Out-of-plane maintenance maneuver:**  $\Delta V$  is applied along the spacecraft orbit angular momentum vector (normal direction) at the orbit ascending or descending node to change the orbit inclination. This type of maneuver is used to control the orbit Local Mean Solar Time.
- **Combination maintenance maneuver:** A combination maintenance maneuver contains both in-plane and out-of-plane  $\Delta V$  components and is used to simultaneously control orbit semimajor axis and orbit inclination.

Both the Local Mean Solar Time (LMST) requirement and the phasing requirement can be satisfied via maneuvers designed in a nominal in-plane or out-of-plane burn attitude configuration (or a combination of the two).

### A. Maneuver Design

#### 1. Orbit Change Maneuver (OCM) Design

The MRO orbit LMST is maintained via small changes in orbit inclination which causes the orbit LMST to drift within the required control band (3:00 PM  $\pm$  15 minutes). MRO has implemented a single OTM (February 2009) to control the orbit LMST since the start of the Primary Science Phase. An inclination change maneuver is most efficiently performed at an orbit ascending or descending node; the maneuver is applied along the orbit angular momentum vector.

The secular node rate may be approximated due to  $J_2$  perturbation only. The rate of change can be controlled via control of orbit inclination. The timing interval between the maneuver epoch and the target epoch determines the rate change needed; the nodal rate change can be transformed into a LMST rate change.<sup>9</sup>

$$\dot{\Omega} = -\frac{3nR_p^2 J_2}{2p^2} \cos i \quad (1)$$

The impulsive  $\Delta V$  to implement a desired inclination change, for a desired nodal rate change, can be accomplished in the burn RTN frame via an out-of-plane  $\Delta V_c$ . The maneuver is ideally performed at  $u = \omega + v = 0$ , at the orbit ascending or descending node.

$$\Delta i = \Delta V_c \frac{r \cos u}{na^2 \sqrt{1 - e^2}} \quad (2)$$

Equation 2 provides an analytical estimate of the maneuver magnitude needed to achieve a desired orbit inclination change. In operations, the designed impulsive  $\Delta V$  magnitude is simulated as a finite maneuver for trajectory integration; the maneuver magnitude is adjusted iteratively through simulation until the desired inclination correction (and desired LMST at some future epoch) is obtained.

#### 2. Orbit Synchronization Maneuver (OSM) Design

Orbit phasing is implemented in the same manner as a nominal GTW maintenance maneuver. An OSM will target a desired accumulated event timing change (orbit phasing, or  $\Delta T$ ) at some future epoch. The magnitude of the total change in orbit period desired by the maneuver can be determined by dividing the

total desired phasing change by the number of orbits between the maneuver epoch and the desired future event epoch. This is the period change per orbit that the maneuver is to perform ( $\Delta P$ ).

$$\Delta P = \frac{\Delta T}{\# \text{ of orbits}} \quad (3)$$

A period change that is positive indicates that the spacecraft must “slow down” to arrive at the desired target later than if left on the nominal trajectory; this can be accomplished by an orbit semimajor axis raise (period increase). A period change that is negative indicates that the spacecraft must “speed up” to arrive at the desired target earlier than if left on the nominal trajectory; this can be accomplished by an orbit semimajor axis decrease (period decrease). For MRO, a “slow down” strategy is favorable as it naturally maintains the orbit Ground Track Walk and also places the MRO spacecraft in a slightly less dense atmospheric regime. For a low-eccentricity orbit, an orbit period change can be approximated as a function of some change in orbit semimajor axis.

$$P = 2\pi\sqrt{\frac{a^3}{\mu}} \Delta P = 3\pi\sqrt{\frac{a}{\mu}} \Delta a \quad (4)$$

The work done by a force (a propulsive maneuver) over a small time interval alters the orbit energy.<sup>9</sup> For a MRO OSM, all work is performed tangent to the orbit (performed along the orbit velocity vector) such that the vector dot product becomes a scalar product.

$$\Delta\xi = \vec{F} \cdot \text{distance} = \vec{F} \cdot \vec{v}\Delta t = -F_T v \Delta t = v \Delta v \quad (5)$$

A change in orbit energy due to a change in semimajor axis is obtained using the definition of orbit energy.

$$\xi = -\frac{\mu}{2a} \rightarrow \Delta\xi = -\frac{\mu}{2a^2} \Delta a \quad (6)$$

The two expressions for  $\Delta\xi$  (Equation 5 and Equation 6) can then be equated to obtain a change in velocity (in the orbit tangential direction) as a function of the change in orbit semimajor axis.

$$v \Delta v = -\frac{\mu}{2a^2} \Delta a \quad (7)$$

Alternatively, the change in velocity is expressed as a change in orbit period in terms of orbit characteristics only. The  $\Delta V$  to accomplish the period change  $\Delta P$  desired in Equation 3 is directly obtained.

$$\Delta V = \frac{1}{6\pi} \frac{1}{v} \sqrt{\frac{\mu^3}{a^5}} \Delta P \quad (8)$$

The methodology described provides an analytical estimate of the maneuver magnitude needed to achieve a desired phasing change. In operations, the designed impulsive  $\Delta V$  magnitude is simulated in trajectory integration as a finite maneuver; the maneuver magnitude is adjusted iteratively through simulation until the desired phasing correction is obtained.

## B. Maneuver Opportunities

MRO Navigation must schedule propulsive maneuvers with consideration for other spacecraft activities and operational constraints. Operational convenience (for maneuver monitoring and post-maneuver spacecraft ephemeris updates) is an important driver for maneuver placement. Regarding science operations, propulsive maneuver dates are desired to not conflict with a set of CRISM (Compact Reconnaissance Imaging Spectrometer for Mars, a MRO science instrument) bi-monthly observations. Pre-MSL launch, MRO Navigation provided a set of nominal OTM opportunities for potential OCM and OSM use (1 opportunity every 2-week MRO spacecraft background sequence until June 2012, when maneuver opportunities occur weekly); the dates of all maneuver opportunities are shown in Table 3. Pre-MSL Launch, MRO Navigation baselined select opportunities (February 1, June 20 and July 18) as the nominal maneuver opportunities.

Table 3: OSM Opportunities Prior to MSL EDL.

Days Prior to MSL Entry	Date	Days Prior to MSL Entry	Date	Days Prior to MSL Entry	Date
201 days	01/18/2012	117 days	04/11/2012	47 days	06/20/2012
187 days	02/01/2012	103 days	04/25/2012	40 days	06/27/2012
173 days	02/15/2012	89 days	05/09/2012	33 days	07/04/2012
159 days	02/29/2012	75 days	05/23/2012	26 days	07/11/2012
145 days	03/14/2012	61 days	06/06/2012	19 days	07/18/2012
131 days	03/28/2012	54 days	06/13/2012	12 days	07/25/2012
				<b>MSL Entry</b>	08/06/2012

### C. Trajectory Down-track Timing Uncertainty

MRO operates in the lowest science orbit altitude configuration (255 km  $\times$  320 km) ever flown at Mars by an orbiting spacecraft. As a result, atmospheric drag is a significant perturbation to the nominal trajectory. MRO Navigation utilizes a timing uncertainty model to generate  $3\sigma$  down-track timing uncertainty over a given propagation period. MRO Navigation models four error sources for short- and long-term down-track timing errors. These timing errors, and their associated growth characteristics, are: atmospheric drag  $\Delta V$  per orbit (white noise term, linear growth and bias term, quadratic growth), unbalanced component of angular momentum desaturation (AMD) x-wheel events (quadratic growth), orbit determination (OD) solution period error (linear growth) and maneuver execution error (linear growth). Linear growth terms impart a period error every orbit and quadratic growth terms impart a period error that is compounded every orbit. Flight experience during the PSP, ESP and EM, flight experience during orbit phasing for the Mars Phoenix mission, and predicted MRO trajectory and Mars atmosphere characteristics were used to evaluate and update model parameters.

#### 1. Atmospheric Drag

Atmospheric drag is the primary perturbation contributing to down-track timing uncertainty. MRO Navigation uses the NASA Marshall Space Flight Center Mars-GRAM (Mars Global Reference Atmospheric Model) 2005 (Mapping Year 0) model for atmospheric modeling (areoid).<sup>8</sup> Navigation estimates the atmospheric drag  $\Delta V$  imparted on the spacecraft every orbit via a stochastic parameter (a Density Scale Factor, or DSF). The DSF is used to scale the value predicted using Mars-GRAM to the observed (reconstructed) atmospheric drag  $\Delta V$  per orbit. The atmospheric drag uncertainty model includes both a white noise (orbit-to-orbit variation) term and a constant bias term; the white noise variations are treated as a linear growth term and the bias is treated as a quadratic growth term (dominant effect). MRO Navigation uses a figure of 105% variation ( $3\sigma$ ) for orbit-to-orbit atmospheric drag  $\Delta V$  variations and a figure of 30% ( $3\sigma$ ) for a constant atmospheric drag  $\Delta V$  bias. These figures were re-assessed using 3 years of low-density season reconstructed MRO trajectory data and are consistent with the observed atmospheric variations.

#### 2. Angular Momentum Desaturation (AMD) Events

AMD events are typically performed once every 2-3 days to desaturate the spacecraft reaction wheels. The thruster pairs used for desaturation are nominally balanced (zero net  $\Delta V$  imparted on the spacecraft), though in reality a small residual error is experienced in flight. The specification requirement is that the spacecraft is to be designed such that the  $\Delta V$  uncertainty due to momentum management shall be less than 0.4 mm/sec ( $3\sigma$ ) per axis per event (this requirement applies to predicted values up to 10 days in advance). This figure, given past flight experience, was increased to  $\Delta V_x = 0.7$  mm/sec/event,  $3\sigma$ , for the Mars Phoenix mission phasing analysis. AMD errors are treated as a quadratic growth term. The  $\Delta V_x = 0.7$  mm/sec/event,  $3\sigma$ , figure was re-assessed using all AMD events since March 13, 2011 (desats located near orbit periapsis); the observed variations are consistent with (and are slightly less conservative than) the  $\Delta V_x$  figure used.

### 3. Maneuver Execution Errors

A Gates model is used to model execution errors for propulsive maneuvers. The magnitude component (fixed magnitude and proportional magnitude errors) of the Gates model contributes to down-track timing error; maneuver execution error timing error growth is linear. For small maneuvers (as anticipated for the final phasing maneuver correction), the fixed magnitude error is 2 cm/sec ( $\sigma_{mag}$ ) and the proportional magnitude error is 2% ( $\sigma_{prop}$ ) ( $3\sigma$ ). Down-track timing is primarily impacted by magnitude error (pointing errors are ignored in this analysis); the  $\Delta V$  contributing to down-track timing error is computed via root-sum-square (RSS):

$$\Delta V_{error} = \sqrt{\sigma_{mag}^2 + \sigma_{prop}^2 \Delta V^2} \quad (9)$$

Typical maneuver execution errors encountered during MRO Operations have proved to be much more accurate than the Gates model requirements and are typically less than 1% of the desired maneuver magnitude. Per reconstructed maneuver analysis, the fixed magnitude error used for down-track timing uncertainty was reduced to 5 mm/sec.

### 4. Orbit Determination Period Errors

The orbit determination solution itself intrinsically contains timing errors; a reasonable value of 0.003 seconds/orbit is used given MRO PSP flight experience. This value was used for Phoenix timing error analysis as well. The OD solution period timing error is small compared to other timing uncertainty sources.

## D. Trajectory Down-track Timing Uncertainty Model

The timing error sources and contributing growth terms are summarized in Table 4. To perform the computation, all velocity errors previously described are converted to period errors using the MRO orbit period. The individual uncertainties are combined via (RSS) to yield the anticipated  $3\sigma$  timing uncertainty model.

$$\Delta t = \sqrt{\Delta t_{Atm,bias}^2 + \Delta t_{Atm,white}^2 + \Delta t_{AMD}^2 + \Delta t_{mnvr}^2 + \Delta t_{OD}^2} \quad (10)$$

Table 4: Down-Track Timing Uncertainty Components.

Model	Value Used	Frequency	Growth Trend
Atm Drag	0.15 mm/sec/orbit	Every orbit	quadratic, linear
AMD Event	0.7 mm/sec/event	Every 2 days	quadratic
Maneuver (OSM)	0.10 m/sec	Once	linear
OD (state estimate error)	3.00E-03 sec/orbit	Once	linear

The timing error model is used to predict short-term timing uncertainty divergence and long-term timing uncertainty convergence. Short-term error growth is used extensively for placement of the final phasing maneuver. Timing error growth over a 40-day period (including a tracking data cut-off (DCO) bias of 7 days following propagation start) is shown in Figure 1. The down-track timing uncertainty, mapped to the MSL Entry event, is not below the  $\pm 30$  second phasing requirement until  $\approx 33$  days prior to MSL Entry. MRO Navigation recommends performing the final phasing maneuver no earlier than the date at which the  $3\sigma$  down-track timing uncertainty is less than the  $\pm 30$  second phasing requirement. Long-term error convergence is used for placement of the initial phasing maneuvers. Timing error convergence from the time of MSL launch (trajectory uncertainty mapped to the MSL Entry event) up to MSL Entry is shown in Figure 2. When performing early phasing maneuvers, MRO Navigation biases the maneuver target away from the requested phasing targets by a timing offset approximately equal to the predicted down-track timing uncertainty. This bias potentially ensures that the final phasing conditions will not be overshoot. The long-term accuracy of the MSL-requested target conditions (previously discussed) is also shown in Figure 2.

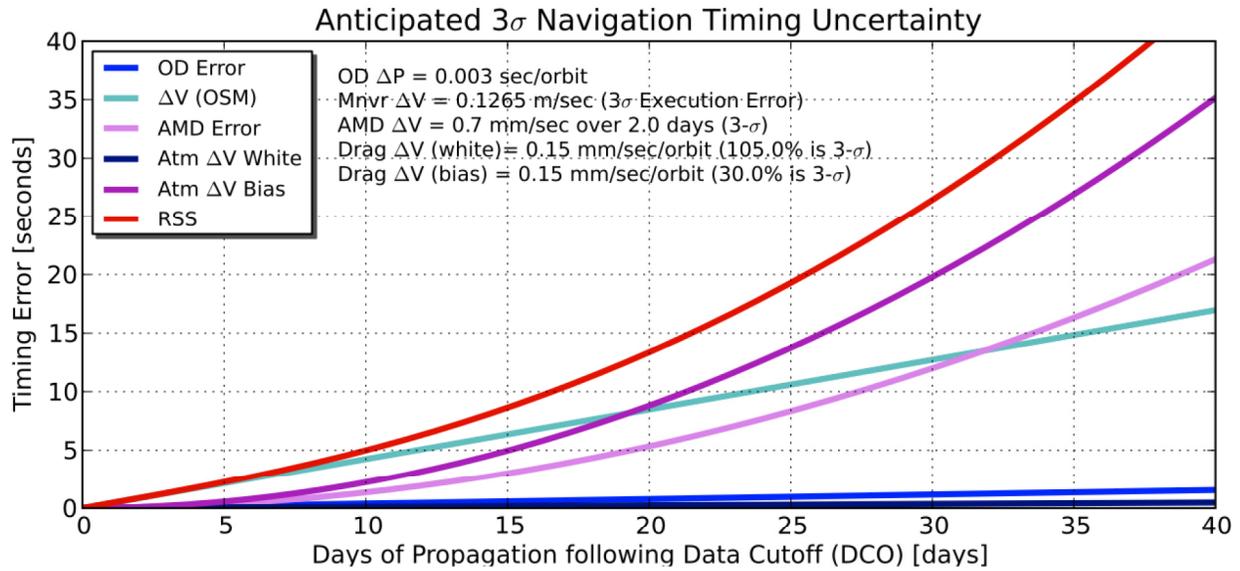


Figure 1: Down-Track Timing Uncertainty: Short-Term Divergence.

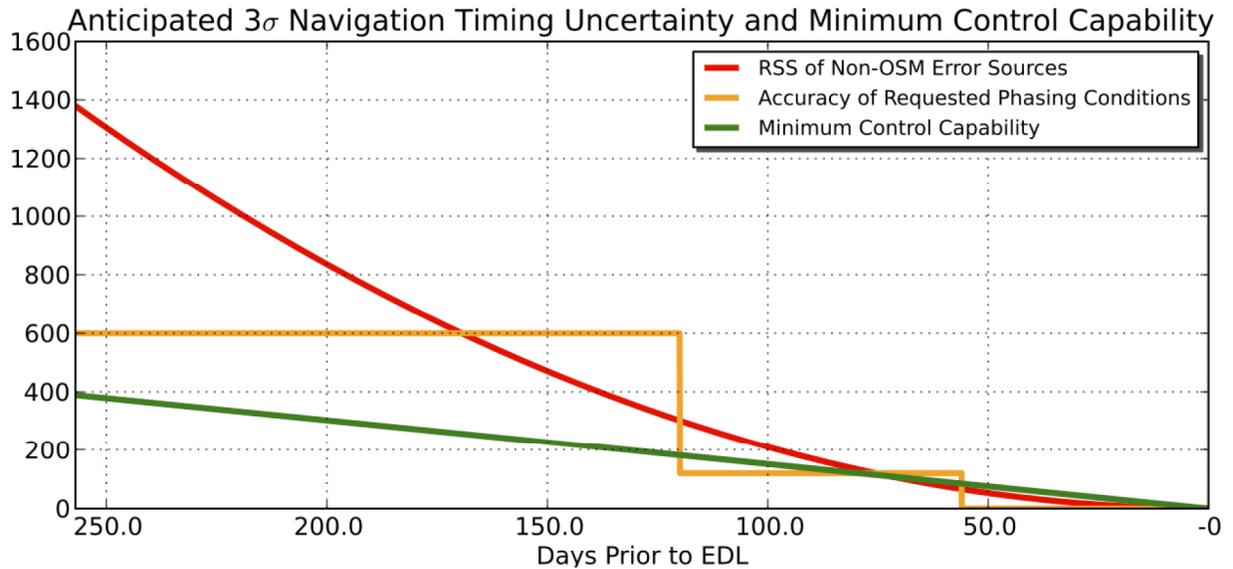


Figure 2: Down-Track Timing Uncertainty: Long-Term Convergence.

### E. Maneuver Placement With Respect To Timing Uncertainty

The transfer time to Mars is a primary driver for the first phasing maneuver in the MRO orbit synchronization campaign, as MRO Navigation will not begin to phase the PSO until post-launch. The shorter (Type 1) transfer to Mars prevents very early maneuvers from being performed in the same manner as was performed for the Phoenix mission (a Type 2 transfer). The longer transfer for Phoenix allowed MRO additional time to implement early phasing maneuvers. Per the MSL launch period and the available maneuver opportunities, the earliest nominal phasing maneuver that can reasonably be performed to target post-launch entry targets is January 3, 2012. The final phasing maneuver should not be performed no earlier than the date prior to

MSL EDL at which the  $\pm 30$  second phasing requirement is violated by the down-track timing uncertainty model. The earliest final maneuver that may be performed without violating the  $\pm 30$  second requirement,  $3\sigma$ , per the timing error model analysis and the available maneuver opportunities, is July 11, 2012.

Table 5: Down-Track Trajectory Timing Uncertainty at Candidate Final Phasing Maneuver Dates.

OSM Date	DCO Date	DCO Prior to MSL EDL	$3\sigma$ Timing Uncertainty <sup>1</sup>	$3\sigma$ Timing Uncertainty <sup>2</sup>
06/20/2012	06/13/2012	53.6 days	65.0 sec	67.8 sec
06/27/2012	06/20/2012	46.6 days	49.2 sec	51.8 sec
07/04/2012	06/27/2012	39.6 days	35.5 sec	37.9 sec
07/11/2012	07/04/2012	32.6 days	24.0 sec	26.2 sec
07/18/2012	07/11/2012	25.6 days	14.8 sec	16.6 sec
07/25/2012	07/18/2012	18.6 days	7.8 sec	9.1 sec
08/27/2012	07/25/2012	11.6 days	3.1 sec	3.6 sec

1. No OSM is included in timing uncertainty analysis
2. OSM of  $\Delta V = 0.1$  m/sec is included on the OSM date

The  $3\sigma$  timing errors mapped to the MSL Entry event (for a given maneuver epoch) can be used to compute the statistical “odds of success” of achieving the  $\pm 30$  second requirement for a final phasing maneuver placed on a given epoch (if a Gaussian (normal) distribution is assumed). This is tabulated in Table 6. The “odds” of exceeding the  $\pm 30$  second requirement are shown for the predicted model; these values were compared to the timing error (predicted vs reconstructed trajectory) of low-density season predicts and were found to agree fairly well. A final phasing maneuver placed on the earliest opportunity (June 20, 2012) has about a 1:4 chance of exceeding the  $\pm 30$  second requirement. Waiting two weeks, until July 4, 2012, to execute the final phasing maneuver reduces these odds to about 1:50; waiting an additional week (to July 11, 2012) guarantees, to greater than  $3\sigma$ , that the  $\pm 30$  second requirement will be satisfied by the final phasing maneuver and no additional (contingency) correction will be needed.

Table 6: “Odds of Success” of the Final Phasing Maneuver.

	OSM3 Date:	06/20/ 2012	06/27/ 2012	07/04/ 2012	07/11/ 2012	07/18/ 2012	07/25/ 2012
OSM Timing (Prior to EDL)	days	46.6	39.6	32.6	25.6	18.6	11.6
DCO (Prior to EDL)	days	53.6	46.6	39.6	32.6	25.6	18.6
$3\sigma$ Uncertainty	seconds	76.2	58.1	42.2	29.2	18.1	10.1
$n\sigma = \pm 30$ seconds?	n	1.18	1.55	2.13	3.08	4.97	8.91
% of Gaussian Distribution	%	76.2%	87.9%	96.7%	99.8%	100.0%	100.0%

1. No OSM is included in timing uncertainty analysis
2. OSM of  $\Delta V = 0.1$  m/sec is included on the OSM date

## F. Contingency Maneuvers

A contingency phasing maneuver, to accommodate a missed final phasing maneuver or a dramatic change in orbit phasing following the final phasing maneuver, is placed at a nominal OSM opportunity just prior to the MSL Entry event (MSL Entry-12 days, on July 25, 2012). At the approximate epoch of the contingency maneuver, the minimum spacecraft control capability (0.02 m/s) yields a phasing control capability of approximately 17.6 seconds, which is less than the phasing control requirement of  $\pm 30$  seconds. A phasing maneuver at MSL Entry-5 days (the last nominal Wednesday OTM slot), though it provides a phasing control capability of approximately 7.0 seconds, is not considered due to the close proximity of this maneuver epoch to the MSL Entry event.

## V. Operational Implementation and Performance

MSL launched from the Space Launch Complex 41 at Cape Canaveral Air Force Station on November 26, 2011. Following MSL launch, the post-launch EDL Relay Targets File was delivered to MRO Navigation by MSL Navigation on December 1, 2012. The predicted MRO trajectory LMST was within the specified LMST target; no inclination change maneuver would be required. The phasing error between the post-launch targets and the predicted MRO trajectory was approximately 75 minutes; orbit phasing would be required. The phasing difference between the predicted MRO trajectory and the MSL-requested latitude at the time of MSL Entry is visualized in Figure 3.

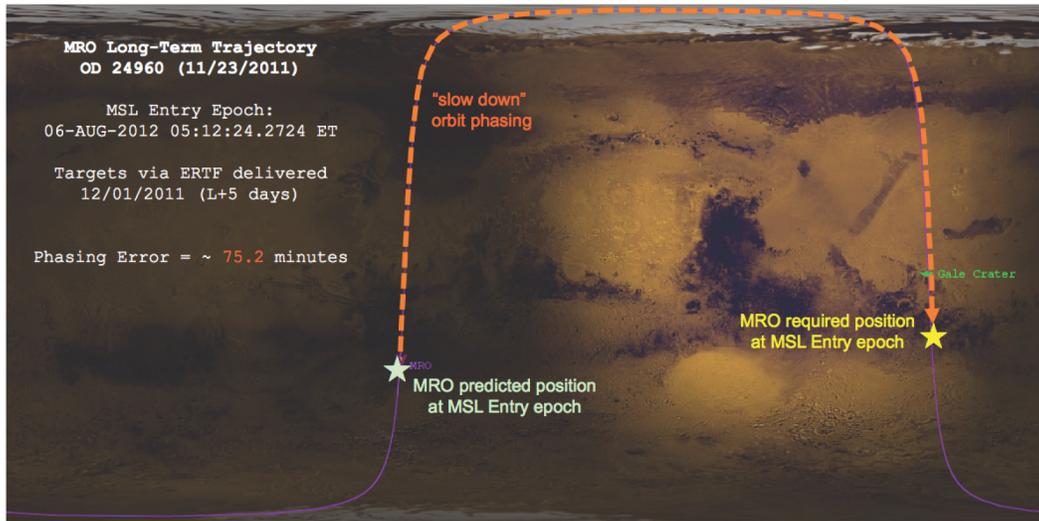


Figure 3: Phasing of MRO Orbit Relative to Post-MSL Launch Target Conditions.

### A. Post-Launch Strategy

The phasing maneuver locations were selected from opportunities described in Table 3. Given the large initial phasing error at MSL launch, a three-maneuver strategy was appropriate. The first maneuver (OSM1), placed on February 1, 2012 (Entry-187 days), would remove a large portion of the orbit phasing error. OSM1 would target to no closer than the  $3\sigma$  timing uncertainty of the trajectory at the date of execution (a bias of approximately 13.5 minutes). OSM1 would target to the latest available target conditions, and would also be used to control the orbit GTW repeat error. The second maneuver (OSM2), placed on June 20, 2012 (Entry-47 days), would remove most of the remaining phasing error and would also be biased away from the latest available target conditions by (at minimum) the  $3\sigma$  timing uncertainty of the trajectory associated with that maneuver date. The OSM2 maneuver magnitude would be chosen such that the final OSM magnitude is not below the minimum spacecraft control capability (2 cm/sec  $\Delta V$ ). The final phasing maneuver (OSM3), placed on July 18, 2012 (Entry-19 days), would remove all remaining phasing error. OSM3 targets to the final phasing conditions, specified in an ERTF file delivered at Entry-56 days.

### B. Implementation

The maneuvers implemented are described in Table 7. OSM1 (OTM-26) was implemented on February 1, 2012 (as planned) and removed approximately 36.5 minutes of orbit phasing error. OSM1 was an apoapsis raise maneuver that increased the orbit period, targeting towards the requested phasing conditions via a “slow down” strategy. MRO Navigation kept close track of Mars atmospheric behavior during early 2012 to appropriately size and place OSM2 and OSM3. Due to decreased atmospheric drag  $\Delta V$  per orbit than that originally anticipated (the phasing offset decreased due to target change and the orbit evolution), the phasing error in early June 2012 was much lower than previously expected. Thus, OSM2 was elected to be cancelled and the final phasing maneuver (OSM3) would remove all remaining phasing error. The date of

OSM3 (originally planned for July 18, 2012) was shifted to July 13, 2012 to appease the MRO project and to accommodate Mars Odyssey spacecraft activity. OSM3 (OTM-27) was performed on July 13, 2012. OSM3 was also an apoapsis raise maneuver that increased the orbit period. As of publication, the July 13, 2012 trajectory phasing error with the ERTF-specified final target conditions was -11.3 seconds (the spacecraft arrives at the requested conditions slightly late). The final trajectory phasing error will be assessed using the reconstructed MRO trajectory post-MSL landing.

Table 7: MRO Orbit Synchronization Maneuvers.

	<b>OSM1</b>	<b>OSM2</b>	<b>OSM3</b>
Date	02/01/2012	06/20/2012	07/13/2012
Days Prior to MSL Entry	187	47	24
Magnitude	0.1500 m/s		0.1265 m/s
Phasing Error Pre-Maneuver	48.9 minutes	<i>cancelled</i>	225.0 seconds
Phasing Error Post-Maneuver	12.4 minutes		-11.3 seconds
Down-track Timing Uncertainty	13.5 minutes	56.8 seconds	22.2 seconds
MRO LMST at MSL Entry	02:57:50 PM	02:57:55 PM	02:57:55 PM

The operational performance of the MRO trajectory as compared to the MSL-specified targeting conditions is shown in Figure 4. Every MRO Navigation orbit determination solution since MSL launch is assessed (MRO Navigation currently produces 2× weekly OD solutions). The phasing error (in minutes), compared to the latest available ERTF solution at the time, is plotted. The down-track timing uncertainty (mapped to the MSL Entry epoch) per the OD solution date is plotted as uncertainty bars. The MRO Navigation Density Scale Factor (DSF) that is applied to the nominal Mars-GRAM 2005 atmospheric model is also plotted as comparison to observed orbit phasing trending; the DSF varied between 0.38 and 1.00 during the period of MSL support. MRO Navigation observed that the orbit phasing error decreased with decreasing atmospheric drag  $\Delta V$  per orbit (decreasing DSF). The observed behavior of the orbit phasing highlights the necessity of performing orbit phasing maneuvers just prior to the desired phasing epoch. If all phasing error was removed using OSM1, the final phasing conditions would have been far overshoot. Additional propellant would have then been required to correct back to the desired phasing condition.

### C. MSL Support Impact on the MRO PSO

MRO Navigation desired, if possible, to maintain the nominal PSO during the MSL orbit phasing campaign. The MRO GTW repeat error (Figure 5) is nominally maintained between  $\pm 40$  km. OSM1 successfully kept the orbit GTW repeat error within the desired control band. The orbit GTW repeat error was allowed to drift outside the +40 km band prior to OSM3 implementation. The GTW repeat error is anticipated to exceed the +40 km control limit prior to OTM-28 (planned for August 29, 2012) that will return MRO to the nominal PSO configuration. Overall, support of MSL via orbit phasing has had minimal impact to the nominal PSO configuration. The frozen orbit condition was also maintained during the MSL orbit phasing support campaign. The MRO frozen condition (Figure 6a) shows the variations in mean argument of periapsis and mean eccentricity MRO has seen over the entire PSP, ESP and EM phases as well as the predicted trajectory for MSL phasing. The variations seen in  $e - \omega$  space for the MSL-phased trajectory are well within the variations seen during the nominal mission. The sun-synchronous condition (3:00 PM orbit LMST at the ascending equator crossing) was unchanged for MSL support (Figure 6b).

## VI. Conclusion

MRO Navigation has designed a flexible maneuver strategy to accomplish the desired target conditions as requested by MSL for Entry, Descent and Landing telecommunication and imaging support. The strategy was desired to be operationally convenient for the spacecraft team and minimally impact MRO science operations occurring well prior to MSL Entry. Post-MSL launch, the maneuver strategy was evaluated with respect to both MRO trajectory and MSL trajectory performance. The down-track timing uncertainty model was used for the initial OSM magnitude sizing and was used to drive the location (timing relative to the MSL Entry

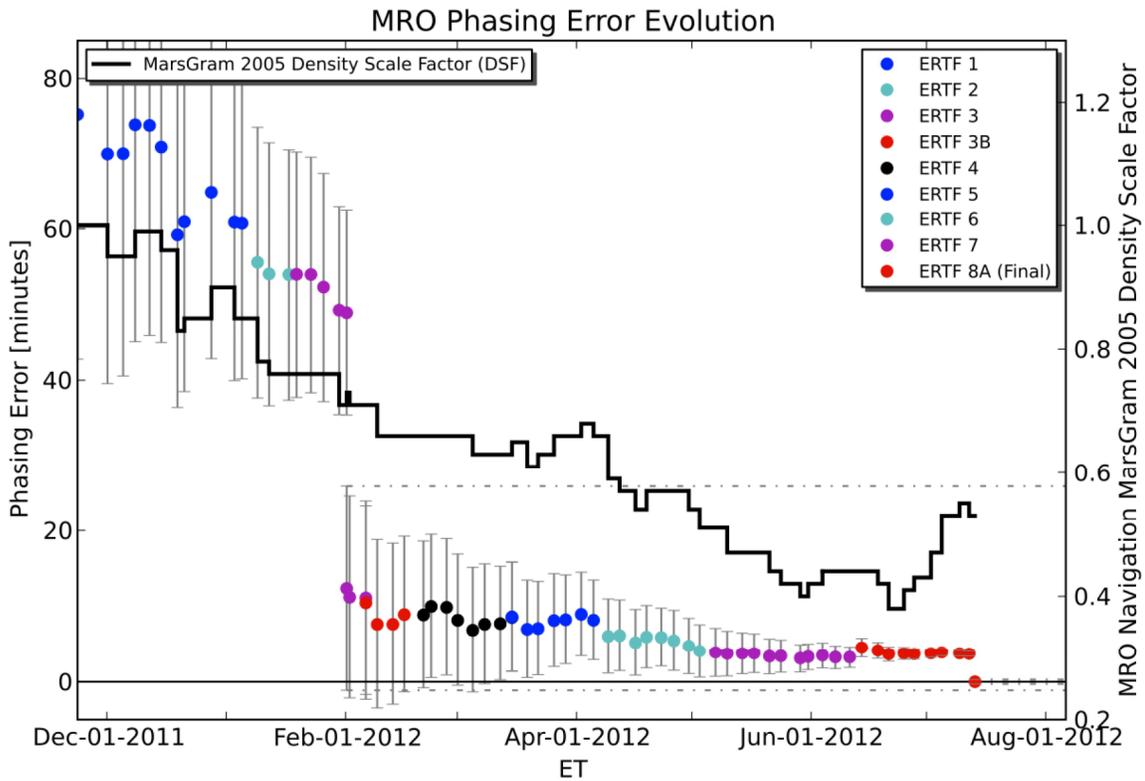


Figure 4: Evolution of the MRO Trajectory Phasing Error Following MSL Launch.

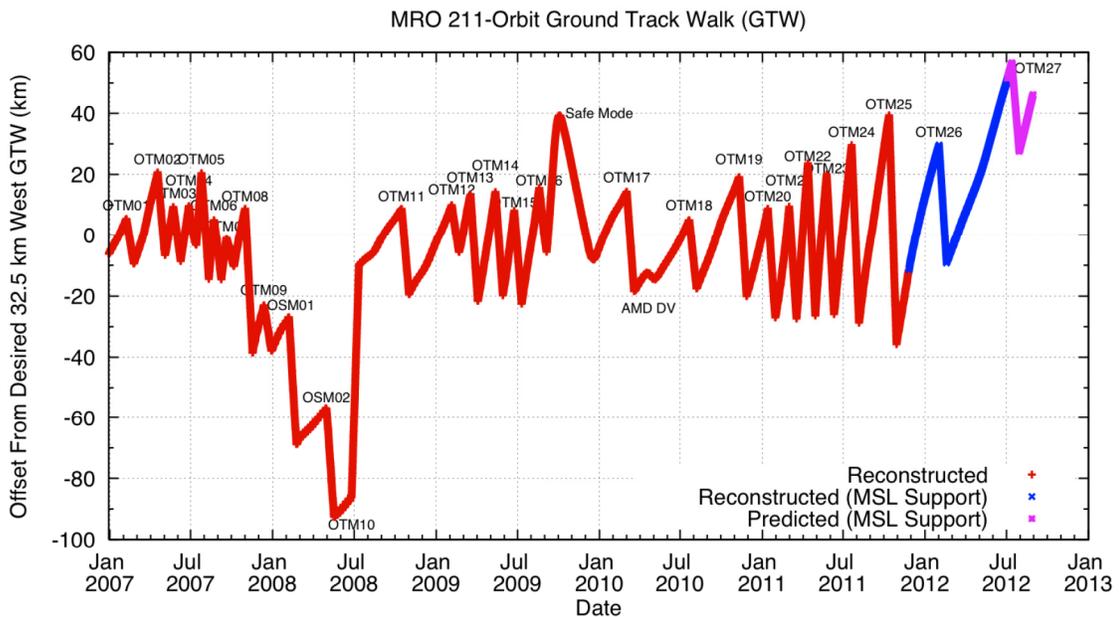
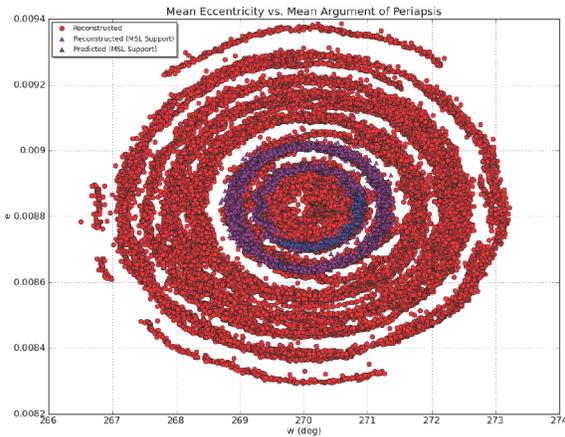
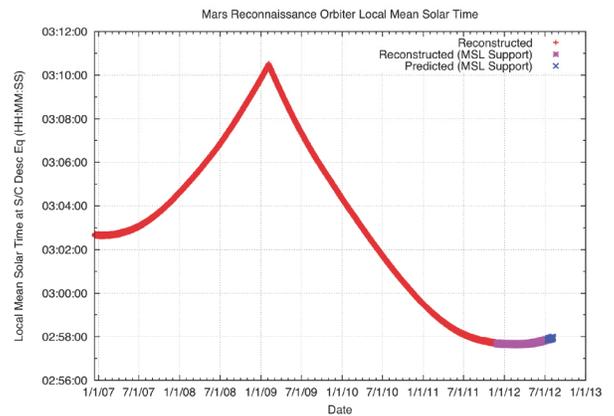


Figure 5: Orbit GTW Repeat Error for MRO Mission.



(a) Orbit Frozen Condition for MRO Mission.



(b) Orbit LMST for MRO Mission.

Figure 6: Predicted MRO PSO Characteristics during the period of MSL EDL support.

event) of the final phasing maneuver. Orbit phasing was accomplished via only two phasing maneuvers that synchronized the MRO orbit down-track timing with the requested target event. These phasing maneuvers, with the exception of a slight violation of the nominal GTW repeat error control bounds, maintained the PSO extremely well. MRO Navigation will assess the final orbit phasing error via trajectory reconstruction following the MSL Entry event. MRO will maneuver back to the nominal PSO configuration following the MSL EDL event. The MRO spacecraft will continue provide telecommunication and imaging support to MSL during its prime mission. MRO will also continue to perform scientific observations at Mars and will continue to be a valuable Mars Program Office asset for current and future Mars missions.

## Acknowledgments

The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Agency.

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