50,000 Laps Around Mars: Navigating the Mars Reconnaissance Orbiter Through the Extended Missions (January 2009 – March 2017)

By Premkumar MENON,[1)] Sean WAGNER,[1)] Stuart DEMCAK,[1)] David JEFFERSON,[1)] Eric GRAAT,[1)] Kyong LEE,[1)] and William SCHULZE[1)]

[1)] *Jet Propulsion Laboratory, California Institute of Technology, USA*

(Received May 25th, 2017)

Orbiting Mars since March 2006, the Mars Reconnaissance Orbiter (MRO) spacecraft continues to perform valuable science observations, provide telecommunication relay for surface assets, and characterize landing sites for future missions. Previous papers reported on the navigation of MRO from interplanetary cruise through the end of the Primary Science Phase in December 2008. This paper highlights the navigation of MRO from January 2009 through March 2017, covering the Extended Science Phase, the first three extended missions, and a portion of the fourth extended mission. The MRO mission returned over 300 terabytes of data since beginning primary science operations in November 2006.

Key Words: Navigation, orbit determination, propulsive maneuvers, reconstruction, phasing

1. Introduction

The Mars Reconnaissance Orbiter spacecraft launched from Cape Canaveral Air Force Station on August 12, 2005. MRO entered orbit around Mars on March 10, 2006 following an interplanetary cruise of seven months. After five months of aerobraking and three months of transition to the Primary Science Orbit (PSO), MRO began science operations in November 2006. Over ten years later, MRO continues to collect valuable science data at Mars and provide critical telecommunication support for surface assets. MRO reached an important milestone completing 50,000 orbits around Mars on March 27, 2017. Previous papers reported on the navigation of MRO from Mars Orbit Insertion (MOI) through the end of the Primary Science Phase (PSP) in December 2008.[1,2] This paper highlights MRO navigation through the extended missions from January 2009 through March 2017, specifically the Extended Science Phase (ESP) and four extended missions. The MRO Navigation Team provided mission support through these mission phases by performing the spacecraft orbit determination (OD) and maintaining the PSO through propulsive maintenance maneuvers. This manuscript also describes the driving performance requirements levied on the Navigation Team and how well those requirements were met during the extended missions.

2. Mission Overview

MRO completed several missions at Mars: the Primary Science Phase, the Extended Science Phase, and three extended missions (EM1, EM2, and EM3). MRO is currently in its fourth extended mission (EM4) which began in October 2016 and ends in September 2018. As an asset of the Mars Exploration Program, MRO continues to perform science observations and provide telecommunication relay support to the Mars Exploration Rover since January 2004 and the Mars Science Laboratory since August 2012.[3)] It also supplied relay support to the Mars Phoenix lander in May 2008, observed the close flyby of Comet Siding Spring at Mars in October 2014[4)] and imaged the ExoMars lander Schiaparelli in October 2016.[5,6)] MRO plans to provide telecommunication support for the Entry, Descent, and Landing (EDL) phase of NASA's InSight mission in November 2018 and NASA's Mars 2020 mission in February 2021.

2.1. 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 MOI and the six Trajectory Correction Maneuver (TCM) thrusters are located along the +Y direction. The large solar panels are on the ±X axes, canted 15 deg towards +Z. The 3-meter diameter High Gain Antenna (HGA) is located opposite the nadir deck, where the majority of the science instruments are located. During science operations, the nadir deck is configured towards Mars. Both solar panels and

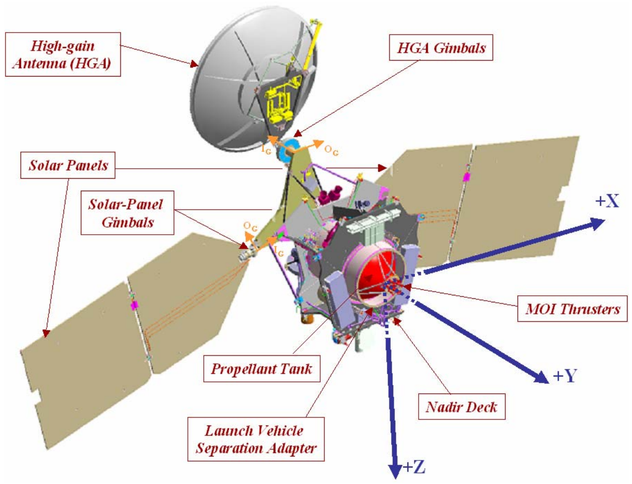

Fig. 1. Diagram of the MRO spacecraft.

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.[7] 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 Orbit Trim Maneuvers (OTMs) 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 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. 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. Among MRO's instruments, high fidelity 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. MRO requires a tight orbital accuracy for operation of HiRISE; this is made more challenging given the variability of the Martian atmosphere. Relay telecommunication support in the UHF frequency range is provided by the Electra payload.

2.2. MRO Primary Science Orbit

The Primary Science Orbit for MRO operations is a 252 km × 317 km altitude, sun-synchronous orbit with the periapsis frozen over the south pole and the ascending node at 3:00 PM ± 15 minutes. The osculating orbital elements for the 50,000th orbit are shown in Table 1. The PSO is designed to exactly repeat after 4602 revolutions in 349 sols 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.

Table 1. MRO osculating orbital elements on March 27, 2017.

Periapsis Epoch: 27-Mar-2017 11:57:51.031 ET	
Semi-Major Axis (a)	3649.2801 km
Eccentricity (e)	0.0057
Inclination (i)	92.5787°
Argument of Periapsis (ω)	269.06956°
Right Ascension of Node (Ω)	235.7435°
True Anomaly (υ)	0.0°
Additional Orbit Information	
Descending Equator Epoch (Start of 50,000th Orbit): 27-Mar-2017 11:30:23.949 ET	
Apoapsis Epoch: 27-Mar-2017 12:53:43.282 ET	
Period (T)	111.55 min
Periapsis Altitude (H_p)	252.1262 km
Apoapsis Altitude (H_a)	318.2174 km

2.3. Navigation Requirements

Navigation is expected to meet long- and short-term prediction requirements in the mission phases. The long-term orbit ephemeris should be sufficiently accurate to select the observations such that the predicted off-nadir pointing will not exceed three degrees in 28 days from the orbit determination data cutoff. The 3-degree uncertainty is equivalent to about 195 km of down-track error or 59 seconds of timing error at the equator. The short-term prediction needs to satisfy 1.5 km of downtrack accuracy, which is about 0.43 seconds in terms of timing uncertainty. To meet these requirements during science operations, the MRO Navigation Team must account for drag from the highly uncertain atmosphere, which is the dominant error source for ephemeris prediction. To minimize the modeling errors of the non-gravitational forces such as atmospheric drag and solar radiation pressure, Navigation also needs the capability to receive and process the quaternion data and small force files to satisfy the spacecraft dynamic models for orbit determination. Table 2 summarizes the navigation requirements which are provided in the MRO Navigation Plan (Reference 7).

Table 2. Summary of Navigation requirements.

	Position - 3σ		
	Downtrack	Radial	Crosstrack
Short-Term Predict	1.5 km	40 m	50 m
Long-Term Predict	195 km (3°)	—	—
Reconstruction	100 m	1.5 m	40 m

3. Navigation System

3.1. Modeling of Spacecraft Dynamics

Accurate modeling of the forces acting on the spacecraft is important for quality navigation. The major forces are:

1. Mars atmospheric drag;
2. Mars gravity field;
3. Location of the planets and Mars satellites, and their perturbations on the MRO trajectory;
4. Solar radiation pressure, which acts on the irregular-shaped spacecraft bus, gimbal-enabled solar array, and high gain antenna;
5. Thruster firings occurring for the momentum buildup desaturation, attitude control, or any unexpected anomalies;
6. Propulsive maneuvers implemented for trajectory/orbit control;
7. Acceleration resulting from the thermal imbalance; and
8. Any unanticipated outgassing

Once MRO entered orbit around Mars, the importance of the modeling of thermal imbalance and outgassing was greatly reduced. The accuracy of the solar radiation pressure also became less critical. For most of the mission, the planetary ephemeris DE-410 was used, which was accurate to several hundred meters. As time progressed, the accuracy of this ephemeris degraded, more recent ephemerides became available, and accurate support for Mars landers became more important. MRO transitioned to DE-421 on June 22, 2016.

During the science mission the important forces which required modeling were the atmosphere, angular momentum desaturations (AMDs), and Mars gravity field. Mars-GRAM (Mars Global Reference Atmospheric Model)[8] was used to model the atmospheric drag effects. Navigation received thruster firing information for AMDs from the Spacecraft Team (SCT) at Lockheed Martin. The thruster pairs are balanced, and thus should impart no net momentum on the spacecraft. However, in practice, they do impart a small ΔV. The information received from SCT was generally not accurate enough to satisfy the high accuracy requirements levied on the Navigation Team. Thus Navigation estimated the AMD ΔVs and used that data to calibrate the information received from SCT.

The many years that Mars Global Surveyor and Mars Odyssey were in orbit provided extensive data with which to enhance the Mars gravity field. However, both orbiters were at significantly higher altitudes than MRO. The MRO95A Mars gravity field included a year of MRO orbit data, up to September 3, 2007. It has been in use by MRO since late 2007.

To model the spacecraft dynamics and observations, JPL's Double Precision Trajectory (DPTRAJ) and Orbit Determination Program (ODP) were initially used for MRO operations. However, the JPL Mission Design and Navigation section developed a replacement to the Navigation software called Monte[9)] (Mission Analysis, Operations, and Navigation Toolkit Environment). After extensive testing, MRO successfully transitioned to Monte in March 2010.

3.2. Filter Setup

Table 2 in Reference 2) shows the estimated parameters and their corresponding 1σ *a priori* uncertainties which were used in the pre-operations covariance analyses. In normal operations a simplified filter setup is desired. The typical estimated parameters were the state, periapsis densities, momentum desaturations, Mars gravity, and solar radiation pressure. The *a priori* sigmas on the state were loose as in the covariance studies (100 km, 10 m/s). The *a priori* sigma on the nominal 1.0 solar pressure scale factor was 0.1 (10%) or smaller. Due to the large orbit-to-orbit variability, a separate density was generally estimated for each orbit. This was achieved by treating the density as a stochastic parameter, with a batch size of one orbit, and estimating for a scale factor on the density calculated by Mars-GRAM. The *a priori* sigma on the density scale factor was 20% of the nominal scale factor.

The AMDs are estimated via a scale factor on the nominal ΔV along each spacecraft axis. This is accomplished by estimating AMDs as stochastic white noise biases, divided into batches based on the momentum wheel being desaturated. When each wheel is desaturated, a different set of balanced thruster pairs are fired.

Even with the improved MRO95A gravity model, some gravity mis-modeling signature was seen in the Doppler residuals. However, only terms in the near-resonant degrees of 12 and/or 13 needed to be estimated to remove the signature. Note that there are 13.2 orbits per sol, so the MRO orbit is near resonant with the degree and order of 13. Since all gravity mis-modeling is absorbed into only a few estimated parameters, the *a priori* is nominally set to 10 to 40 times the MRO95A formal uncertainties. As time progressed from the end of the MRO data arc fit in MRO95A, the *a priori* sigmas had to be increased.

Mis-modeled effects from density, gravity and AMDs can be partially soaked into any one of these parameters. Thus it was important to set the relative filter weighting between these models via the *a priori* sigmas to minimize the possibility of a mis-modeling in one parameter being absorbed in another parameter estimate. These *a priori* sigmas were tuned to reduce such possibilities.

The standard Deep Space Network (DSN) daily tracking allocation for MRO is 12 to 16 hours. When in orbit around Mars, Doppler is the only measurement required due to its strong signature from the orbit being tied to the planet. Two-way X-band Doppler was the main data type used by Navigation. Periodically small arcs of three-way Doppler data were available. They were sometimes included in filter solutions, but de-weighted by 20%. One-way X-band Doppler was also available due to the Ultra Stable Oscillator (USO) on MRO. The MRO USO frequency reference is generated by an oven-controlled crystal oscillator with an approximate stability of 10^{-12} over the Doppler count time. Even so, the one-way Doppler exhibited signatures and was significantly noisier than the two-way Doppler. It was still usable as a supplement to two-way Doppler, and enabled Navigation to fill in gaps between two-way passes, resulting in density scale factor estimates on orbits that otherwise would have had no observability. In filter solutions, the one-way Doppler was de-weighted by at least 50%. One or more sets of frequency bias and rate terms also had to be estimated per tracking pass. During solar conjunction one-way Doppler was especially useful, since two-way Doppler was either not available or extremely degraded. After several years in orbit, the USO became less stable in January 2012 and one-way Doppler was no longer of use for Navigation.

3.3. Navigation Process

The Navigation Team has two major functional groups: Orbit Determination, and Flight Path/Orbit Control and Trajectory Analysis, sometimes referred to as Maneuver Analysis. Trajectory generation is the fundamental process shared by both groups. Thus special long reference trajectories may be generated by either group, although usually it falls to the maneuver analyst due to maneuvers which need to be included. Trending of trajectory behavior, navigation performance, parameter estimates, and real-time spacecraft event monitoring are related work performed by the Navigation Team.

The files which are regularly delivered and used by Navigation include: spacecraft attitude, small forces (AMDs), tracking data, Earth orientation and Earth atmospheric media calibrations. In order to satisfy project requirements, Navigation delivers products twice a week for predicted trajectories and once a week for reconstructed trajectories. The Navigation delivery kicks off the work by the rest of the MRO teams, such as science planning and sequence development. The SPK file is the main Navigation deliverable. It contains the spacecraft ephemeris, converted from the Navigation internal format to the SPK format via NAIF[10)] tools. The other Navigation products are derived from the spacecraft ephemeris. The Orbit Propagation and Timing Geometry (OPTG) file contains information at discrete orbit events (e.g. periapsis). The light-time file contains information on the topocentric light-time between MRO and the DSN stations. It is used by SCT to update the spacecraft clock file, which defines the time conversion between UTC and the spacecraft clock. The Maneuver Performance Data File (MPDF) supplied by SCT gives the spacecraft mass, center of mass, and thrust information required for designing maneuvers. The Maneuver Profile File (MPF) is the Navigation interface to SCT for delivering information on maneuvers to be executed.

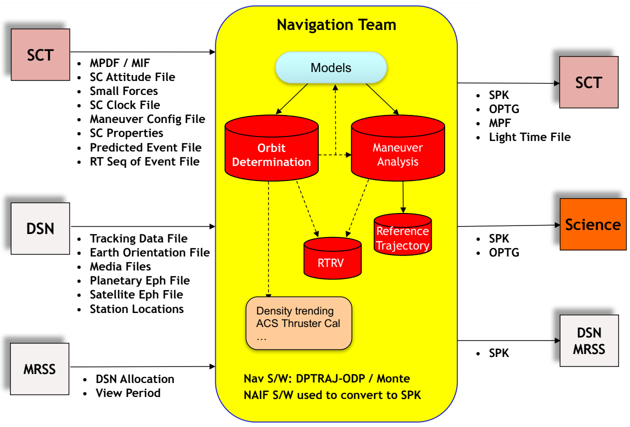

Fig. 2. Simplified navigation process.

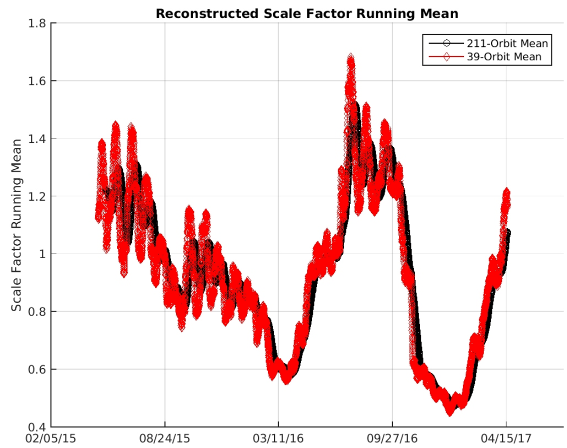

Fig. 3. Reconstructed density scale factor running mean.

3.3.1. Orbit Determination Process

In operations, project deliveries, data trending, maneuver analyses and reference trajectories are all based on orbit determination analyses. As shown in Figure 2, OD starts with a full range of information (data and models) collection. Real-time engineering data including reconstructed spacecraft attitude and on-board small forces due to momentum desaturation are generated through the telemetry query system. Along with the tracking data and other ancillary information provided by the Ground Data System, the OD process is performed through spacecraft dynamic model fine-tuning, data arc and ancillary data setups, and estimation strategy updates.

The DSN schedule determines the availability of MRO Doppler, which determines the time span for the OD analysis. After the most up-to-date information on models and calibrations are retrieved, as shown in Figure 2, an OD solution may be generated via a trajectory integration and filter run. Due to the non-linearity of models, this OD solution must be iterated to convergence by folding in the updated parameter estimates from one solution into the nominal models of the next solution. The converged OD solution can be integrated out to a later date for covariance analysis, maneuver analysis, and trajectory products generation. The trajectory products are delivered to the project to initiate sequence development, science planning, etc.

The results of the OD solutions may also be used for tracking data and model analyses. The history of model parameter estimates may be trended, and if necessary, used for new calibrations of models. The most obvious example is the density. The current OD solution density estimates, along with the previous history, is used to derive the appropriate scale factor to be applied to the Mars-GRAM density when the trajectory is integrated out for a predict delivery. The past long-term estimated density history may also be examined to get insight into the behavior of the atmosphere model. Figure 3 shows the 39-orbit and 211-orbit running mean of the reconstructed Mars-GRAM density scale factor for matching the actual density variations with predictions.

Another important example are the AMDs. Unfortunately, the thruster calibration performed in cruise did not appear to give good results after MOI. Hence Navigation needed to find some way to resolve this problem. A scale factor is estimated for each set of thruster pairs in an OD solution. By combining the information from many analyses, the performance of thruster pairs can be resolved and analyzed to produce a pseudo ACS thruster calibration. Even though this greatly enhanced the desaturation calibration in the science phase, there were limitations to this approach, and calibrations did not necessarily carry over well if quite different desaturation behavior started to occur. Therefore a 100% *a priori* sigma was used for the desaturated estimates.

3.3.2. Flight Path/Orbit Control and Trajectory Analysis

The maneuver analyst is responsible for designing trajectories such that the spacecraft achieves the desired future orbit characteristics. Some examples include controlling the spacecraft ground track walk, controlling the orbit Local Mean Solar Time (LMST), and supporting a Mars lander's EDL sequence. The main support the maneuver analyst provides is the design leading to the execution of upcoming OTMs, and the generation of reference trajectories for long-term project planning. The final design, implementation, verification, and execution of an OTM takes 7–10 calendar days for the MRO project.

3.3.3. Real-Time Residual Viewer

Although not necessary for any project products, the Real-Time Residual Viewer, or RTRV, can be useful for real-time event monitoring, such as a maneuver. For major maneuvers such as MOI or large orbit (inclination) change maneuvers, the project is interested in getting status information on the maneuver as soon as possible. RTRV displays the Doppler residuals, which shows the projected line-of-sight velocity differences, thereby giving immediate information on the deviation of the actual trajectory from the designed maneuver trajectory.

RTRV can also be employed to observe the accuracy of a delivered predicted trajectory, such as a post-validation of a Navigation delivery, since an error in the predict would cause the Doppler residuals to grow quickly. It can also be used to observe the accuracy of the prediction, since the density behavior relative to the expected (modeled future) behavior is the major perturber of the Doppler residuals. In addition, Navigation performs real-time archiving of data from the same DSN feed that RTRV uses. This allows Navigation to use the latest Doppler data in predict analyses, which can be beneficial in meeting the tight short-term predict accuracy requirements.

3.3.4. Automation of Processes

Since May 2014, MRO has been automating the daily quick-look OD solutions via JPL's automation framework tool called TARDIS[11)] (Traceable Automation with Remote Display and Interruptible Scheduler). This paved the way for the Soil Moisture Active Passive (SMAP) mission to utilize TARDIS for their automated predict process. The automation of the MRO trajectory reconstructions began in May 2015, establishing MRO as the first JPL mission to use TARDIS in operations.

4. Navigation Operations and Performance

4.1. Orbit Prediction

Navigation operations include predicting the MRO trajectory for long and short terms. The long-term prediction typically spans at least 28 days from the time of the OD data cutoff. The requirements for the long- and short-term predictions are given in Table 2. During the PSP mission the Navigation Team would deliver the trajectory products at least three times a week. This was reduced to two times per week beginning with the ESP mission while still meeting the timing requirements. The longest stretch between predicted trajectories is usually about five days prior to an onboard ephemeris update (during PSP the longest stretch was about four days due to more frequent updates). Figure 4 shows the timing errors for all predicted trajectories at the end of five days. The dashed blue lines indicate the timing requirement of 0.43 seconds for short-term predictions. Occasional outliers happened due to atmospheric density variability especially during safe modes or high density seasons when the solar longitude (L_s) is near 270°. As seen in Figure 4 the larger errors are generally in the third part of each Mars year near the Southern Summer Solstice ($L_s = 270°$). This behavior is evident also in Figure 5 which displays the long-term timing errors.

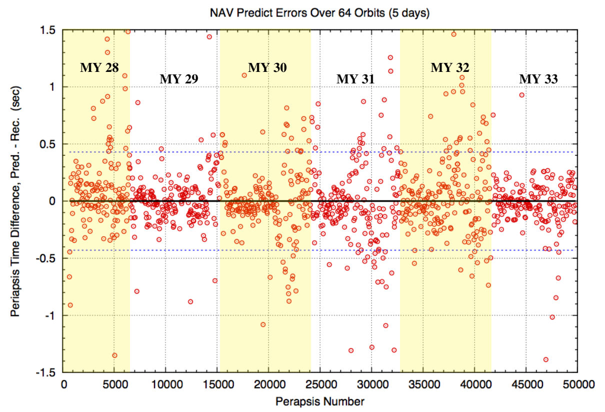

Fig. 4. Short-term predict timing errors vs. orbit over 64 orbits (5 days).

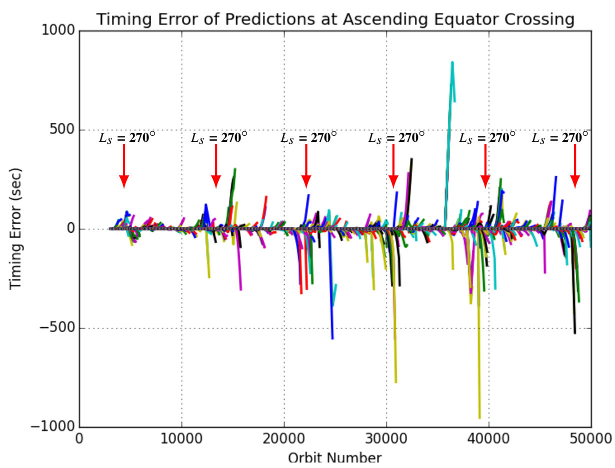

Fig. 5. Long-term predict timing errors vs. orbit since March 2007.

4.2. Orbit Reconstruction

MRO orbit reconstructions are routinely performed to aid science data analysis. For example, Figures 6 and 7 provide the reconstructed apoapsis and periapsis altitudes, respectively, since the 252 km × 317 km science orbit was established in November 2006. It can be seen that both apoapsis and periapsis have been maintained within ±5 km of the nominal values. Reconstruction batches spanning about 1.5 days are processed daily and overlapping trajectories compared to ensure that the requirements are satisfied (see Table 2). Figures 8, 9, and 10 indicate typical comparisons in the radial, tangential (downtrack), and normal (cross-track) directions, where the yellow lines show the solar conjunction periods. Occasional violations occurred during safe modes, solar conjunctions, and Earth beta angle singularity periods. At times of high Earth beta angle (e.g., near a singularity of 90 deg), when the orbit plane is almost perpendicular to the Earth line-of-sight, the spacecraft position in the radial and down-track directions were poorly determined (see Figures 8 and 9). Similarly, the position in the cross-track direction was also deficiently estimated when the Earth beta angle crossed 0 deg four times in the early years of the mission (see Figures 10 and 11). Since the dramatic increase in one-way Doppler data noise (a two-orders of magnitude jump since January 2012) only two-way and three-way Doppler data are currently used for reconstructions. Reconstructions during solar conjunctions were done by anchoring a longer than usual time span of one-way Doppler data with two-way data at both ends. Since May 2015 the Navigation Team has been performing the routine reconstructions via the TARDIS automated process and intervening manually only as needed.

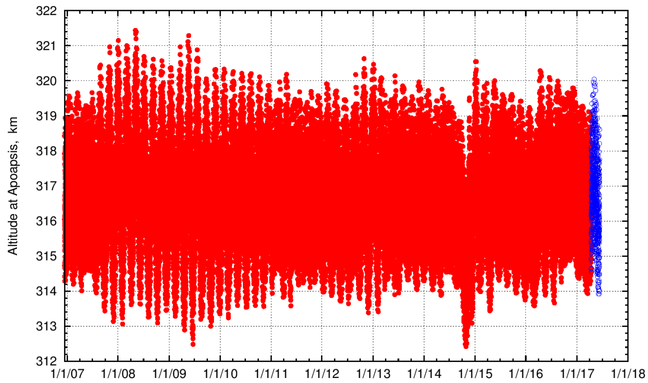

Fig. 6. Apoapsis altitude (reconstructed in red, predicted in blue).

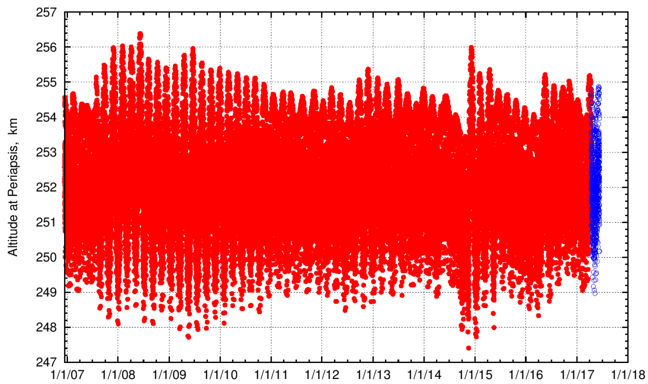

Fig. 7. Periapsis altitude (reconstructed in red, predicted in blue).

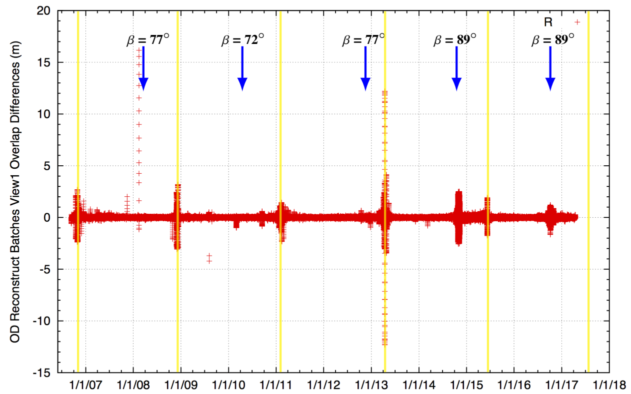

Fig. 8. Reconstruction overlap differences – radial (1.5 m req.).

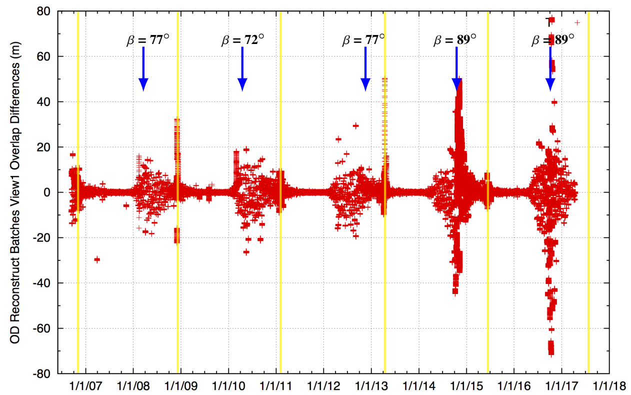

Fig. 9. Reconstruction overlap differences – down-track (100 m req.).

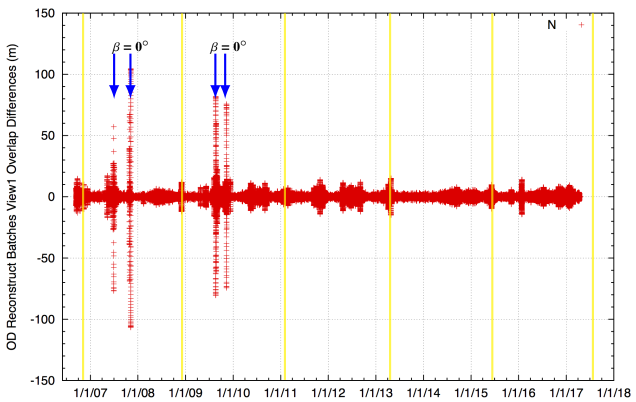

Fig. 10. Reconstruction overlap differences – cross-track (40 m req.).

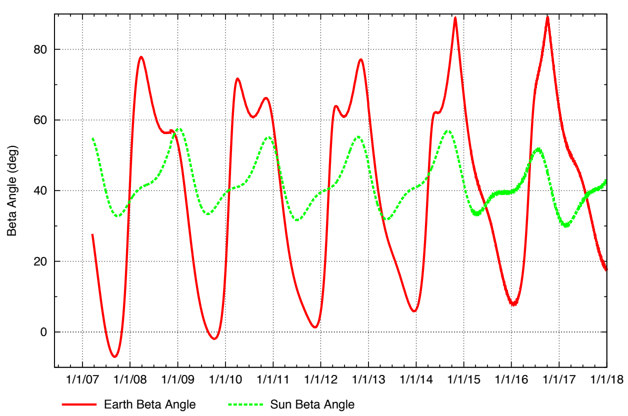

Fig. 11. MRO Earth and Sun beta angles (2007–2018).

4.3. Maneuvers

MRO Navigation has performed OTMs in typically one of two standard maneuver orientations, or a hybrid of the two: in-plane (parallel to the spacecraft velocity vector) or out-of-plane (along the spacecraft angular momentum vector). The burns are executed as fixed-attitude maneuvers and are usually scheduled for the first Wednesday morning of a new two-week spacecraft background sequence starting on Sunday. The 50 maneuvers performed since science operations began in November 2006 are summarized in Table 3. For each maneuver, the table lists the burn date, burn location such as periapsis, apoapsis, or equator crossing (descending or ascending), and the reconstructed maneuver ΔV magnitude. Maneuvers are also grouped according to mission phase as indicated in the table. Depending on the maneuver size, the Spacecraft Team at Lockheed Martin used either a 25% or 75% duty cycle for propulsive burns, the latter of which was utilized for all inclination-change maneuvers performed (OTMs 12, 39, 43, 44, and 48). Also, the minimum maneuver capability of 20 mm/s in ΔV magnitude was considered when designing these maneuvers. Reference 12) provides further details on these OTMs.

Table 3. MRO maneuver history (February 2007 – March 2017). *Note: Inclination-change maneuvers are indicated in bold.*

Orbit Trim Maneuver (OTM) #	Date	Apsis or Node	ΔV Mag. (m/s)	Orbit Trim Maneuver (OTM) #	Date	Apsis or Node	ΔV Mag. (m/s)
PSP — 01-Jan-2007 to 31-Dec-2008				24	20-Jul-2011	Peri	0.2666
01	07-Feb-2007	Apo	0.0711	25	12-Oct-2011	Peri	0.2923
02	18-Apr-2007	Peri	0.1302	26	01-Feb-2012	Peri	0.1521
03	23-May-2007	Apo	0.1128	27	13-Jul-2012	Peri	0.1305
04	27-Jun-2007	Peri	0.1230	28	29-Aug-2012	Peri	0.2591
05	25-Jul-2007	Apo	0.2248	**EM2 — 01-Oct-2012 to 30-Sep-2014**			
06	22-Aug-2007	Peri	0.1416	29	24-Oct-2012	Peri	0.1830
07	19-Sep-2007	Apo	0.0816	30	19-Dec-2012	Apo	0.2953
08	31-Oct-2007	Peri	0.1925	31	13-Feb-2013	Peri	0.2957
09	12-Dec-2007	Apo	0.0764	32	27-Mar-2013	Peri	0.2834
OSM-1	06-Feb-2008	Peri	0.1520	33	05-Jun-2013	Peri	0.4011
OSM-2	30-Apr-2008	Peri	0.1223	34	31-Jul-2013	Apo	0.1990
10	25-Jun-2008	~Apo	0.2485	35	20-Nov-2013	Peri	0.2411
11	15-Oct-2008	Peri	0.1078	36	07-May-2014	Peri	0.3092
ESP — 01-Jan-2009 to 30-Sep-2010				37	02-Jul-2014	Peri	0.0649
12	**04-Feb-2009**	**DEq**	**3.1943**	38	25-Sep-2014	Apo	0.2773
13	18-Mar-2009	Peri	0.1525	**EM3 — 01-Oct-2014 to 30-Sep-2016**			
14	13-May-2009	Peri	0.1627	**39**	**19-Nov-2014**	**DEq**	**3.4597**
15	24-Jun-2009	Peri	0.1589	40	28-Jan-2015	AEq	0.4342
16	19-Aug-2009	Peri	0.1315	41	25-Mar-2015	Peri	0.3239
17	03-Mar-2010	Peri	0.1235	42	20-May-2015	Apo	0.3530
18	21-Jul-2010	Peri	0.0940	**43**	**29-Jul-2015**	**DEq**	**5.3401**
EM1 — 01-Oct-2010 to 30-Sep-2012				**44**	**06-Apr-2016**	**AEq**	**7.9166**
19	10-Nov-2010	Peri	0.1543	45	27-Jul-2016	Peri	0.1921
20	13-Jan-2011	Peri	0.1603	46	14-Sep-2016	Peri	0.2102
21	02-Mar-2011	Peri	0.2160	**EM4 — 01-Oct-2016 to 30-Sep-2018**			
22	13-Apr-2011	Peri	0.2745	47	02-Nov-2016	Apo	0.2241
23	25-May-2011	Peri	0.2364	**48**	**22-Mar-2017**	**DEq**	**3.2032**

4.4. GTW Error Maintenance

Figures 12 and 13 show the reconstructed ground track walk (GTW) repeat error from January 1, 2007 to April 16, 2017, covering 50 maneuvers performed since science operations began in November 2006. During PSP, pro-velocity in-plane maneuvers were used for apsis height control to maintain the PSO GTW repeat error between ±10 km with OTMs 1–10. This GTW error control band was relaxed to ±20 km during ESP with OTMs 11–19, ±30 km in the first half of EM1 with OTMs 20–23, and ±40 km in the second half of EM1 through EM3 with OTMs 24–46. In EM4, the GTW error control band was further loosened to ±60 km beginning with OTM-47.

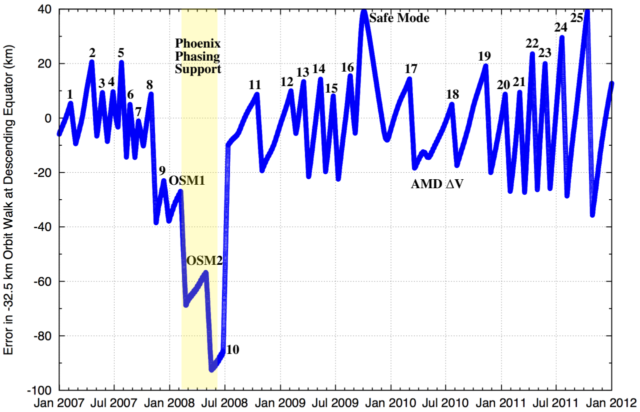

Fig. 12. Reconstructed GTW repeat error from January 1, 2007 to January 1, 2012 (OTMs 1–25).

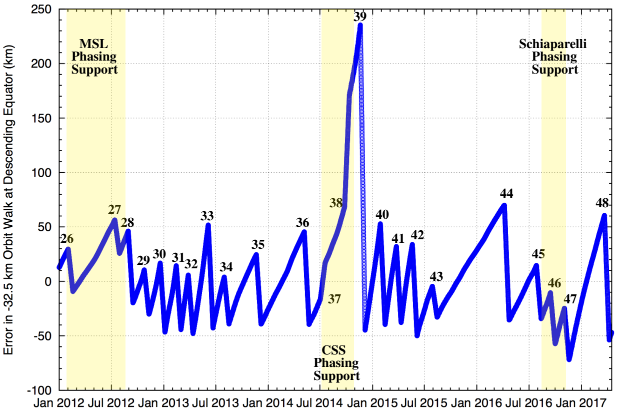

Fig. 13. Reconstructed GTW repeat error from January 1, 2012 to April 16, 2017 (OTMs 26–48).

During the Comet Siding Spring (CSS) risk mitigation period,[4)] two anti-velocity maneuvers were performed which resulted in an unprecedented GTW error of almost +240 km at the time of OTM-39, as seen in Figure 13. In comparison, the GTW errors reached about −90 km during Phoenix EDL support[2)] (Figure 12), about +55 km during the Mars Science Laboratory (MSL) EDL coverage[3)] (Figure 13), and nearly −60 km during the Schiaparelli overflight support period[5)] (Figure 13).

4.5. Frozen Condition Maintenance

The MRO Navigation Team is required to keep the orbit frozen about the Mars South Pole. The mean eccentricity vs. mean argument of periapsis (e-ω) space is used to track this frozen orbit condition. However, there is no specific requirement for how the e-ω curve should be. Navigation currently contains the e-ω variation such that ω varies within 3 deg about 270 deg. For comparison, Mars Global Surveyor had kept e-ω between 263° and 277° (at apoapsis); Mars Odyssey has been within 262° and 278° (at apoapsis). The entire mean e-ω reconstructed history from the beginning of science operations in November 2006 through March 2017 (just prior to the execution of OTM-48) is shown in Figure 14. Reference 12) provides more detail on the effects of each maneuver on the frozen condition.

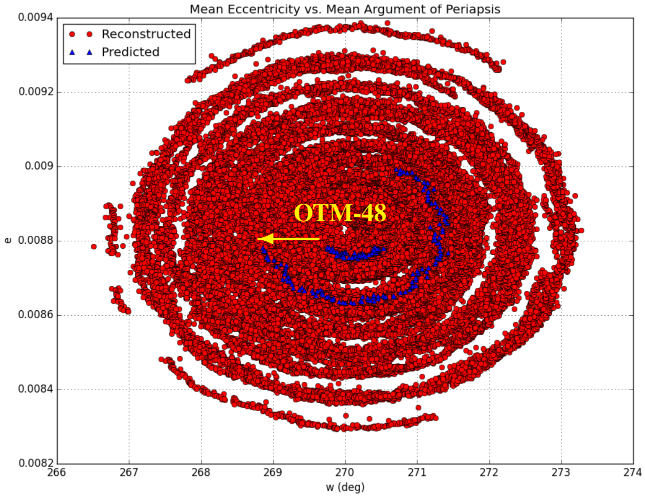

Fig. 14. Reconstructed mean eccentricity vs. mean argument of periapsis from January 2007 – March 2017.

4.6. Orbit Phasing

Orbit phasing is accomplished through in-plane Orbit Synchronization Maneuvers (OSMs). An OSM is used to adjust the MRO orbital period such that, over a given duration, a desired total orbit down-track timing change is produced. Table 4 presents a summary of the phasing offsets that MRO achieved in support of the EDL sequences of Phoenix and MSL in May 2008 and August 2012, respectively, the protected location from the CSS incoming particles in October 2014, and the third overflight of the Schiaparelli landing site in October 2016. As can be seen in the table, the final phasing offsets from the requested target times were well within the phasing requirements. Note that OSMs are OTMs used for phasing and the OSM numbers are reset with each phasing target; OSM-1 and OSM-2 used for Phoenix phasing were the actual maneuver names.

Table 4. Orbit phasing maneuver history.

Phasing Target	Phoenix EDL	MSL EDL	CSS Flyby Safe Location	Schiaparelli 3rd Overflight
2000 IAU Mars Fixed Target Time (SCET)	25-May-2008 23:32:07.0026 ET	06-Aug-2012 05:11:54.5626 ET	19-Oct-2014 20:07:00 UTC	20-Oct-2016 17:17:43.7890 ET
Target Latitude	48.0311 deg	−26.5011 deg	7.6042 deg	−2.05 deg
Pre-OSM Offset	**23.7 min early**	**48.9 min early**	**19.0 min late**	**30.6 min early**
OSM Location	OSM-1	OTM-26 (OSM-1)	OTM-37 (OSM-1)	OTM-45 (OSM-1)
OSM Correction	**20.7 min early**	**36.5 min early**	**9.0 min late**	**20.6 min early**
Post-OSM Offset	2.6 min early	12.4 min early	6.1 min late	9.5 min early
OSM Location	OSM-2	OTM-27 (OSM-3)	OTM-38 (OSM-2)	OTM-46 (OSM-2)
OSM Correction	**3.9 min early**	**3.8 min early**	**8.4 min late**	**9.6 min early**
Post-OSM Offset	2.5 sec early	11.3 sec late	23.7 sec early	2.5 sec late
Requirement	**±30 sec**	**±30 sec**	**±2 min**	**±5 min**
Final Phasing Offset	**0.25 sec early**	**9.0 sec late**	**57.0 sec early**	**10.4 sec late**
Comments	Low density. OTMs 08 & 09 used to reduce ~45 min phasing offset.	Low density. Cancelled OSM-2 on 20-Jun-2012.	High density. Phasing target was arrival time of peak particle fluency.	High density. Phasing target was maximum elevation time at third overflight.
Reference	Highsmith (Reference 2)	Williams (Reference 3)	Menon (Reference 4)	Menon (Reference 5)

4.7. Local Mean Solar Time Control

Out-of-plane maneuvers are implemented to control the LMST drift by changing the inclination. These maneuvers have been used to return MRO to the PSO operating bounds (3:00 PM ± 15 minutes LMST). Inclination-change maneuvers used for EDL support are referred to as Orbit Change Maneuvers (OCMs). Figure 15 shows the reconstructed LMST profile from

January 2007 through March 2017 (in red), as well as the maneuvers that were performed to control the LMST drift.

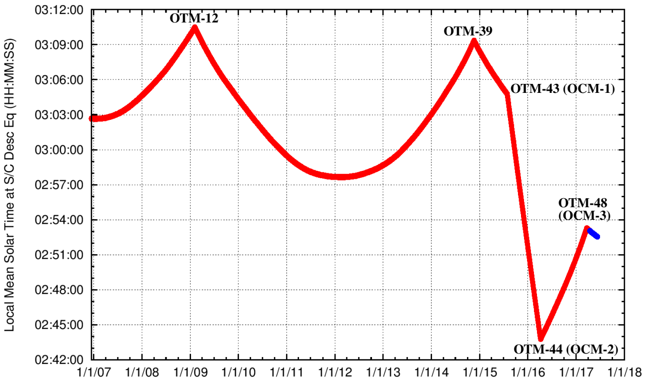

Fig. 15. Reconstructed LMST from January 2007 – March 2017. *Reconstructed (red), predicted (blue).*

Inclination-change maneuvers have been implemented three times in the mission to drift the LMST back towards 3:00 PM at the ascending equator crossing: OTM-12 in February 2009, OTM-39 in November 2014, and OTM-44 in April 2016. The spacecraft is required to operate within a Local True Solar Time (LTST) range of 2:00 PM to 4:00 PM. Hence, the orbit plane change maneuvers were designed complying with this limitation. Three OCMs have been implemented in relation to InSight EDL support. OTM-43 (OCM-1) was performed on July 29, 2015 at the descending equator to change the nodal drift such that 2:30 PM LMST would be achieved on September 28, 2016, the original date for InSight EDL. After the postponement of the InSight launch, OTM-44 (OCM-2) on April 6, 2016 was performed at the ascending equator to re-establish the 3:00 PM LMST PSO configuration. OTM-48 (OCM-3) was performed on March 22, 2017 to arrest the LMST drift such that the InSight EDL 2:52 PM LMST requirement will be met on November 26, 2018. Table 5 summarizes the three OCMs performed thus far for InSight EDL support. The OCM strategies for InSight EDL support are described in Reference 6.

Table 5. OCMs for InSight EDL support.

Maneuver	Maneuver Epoch (UTC-SCET)	ΔV (m/s)	Comments
OCM-1 (OTM-43)	29-Jul-2015 13:21:31	5.34	2:30 PM LMST for InSight EDL in 2016
OCM-2 (OTM-44)	06-Apr-2016 13:31:09	7.92	Return to 3 PM LMST for MRO PSO
OCM-3 (OTM-48)	22-Mar-2017 13:38:40	3.20	2:52 PM LMST for InSight EDL in 2018
	Total	**16.46**	

5. MRO Propellant Consumption

Figure 16 shows the propellant consumed by momentum desaturations, maneuvers, and safe mode events on an annual basis. The annual budget for propellant usage is 15.4 kg: 13 kg for momentum desaturations and 2.4 kg for maneuvers. The large amount of propellant used by the five inclination-change maneuvers performed thus far are reflected in calendar year 2009 and fiscal years 2015–2017 budgets (in red). Also of note is the substantial amount of propellant used for safe modes in calendar year 2009 (in yellow).

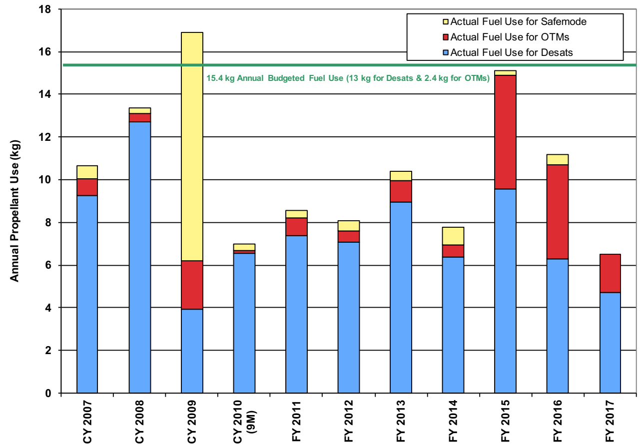

Fig. 16. MRO annual propellant usage (January 2007 – March 2017).

6. Navigation Challenges

The MRO Navigation Team encounters various challenges outside of nominal operations which include solar conjunctions, seasonal dust activity, and potential close approach concerns with other Martian orbiters. During solar conjunction, the Sun-Earth-Probe (SEP) angle becomes significantly small resulting in very noisy tracking data. In the periods when two-way Doppler data is not available (e.g., below 2 degrees SEP), one-way Doppler data, although noisy, is also used. The trajectory prediction will be limited to using pre-conjunction two-way Doppler data. Reconstruction of the trajectory is done by anchoring the two ends of a very long one-way Doppler data arc with two-way Doppler data. Critical activities such as maneuvers are also avoided during a solar conjunction period.

Mars missions experience increased dust activity when the solar longitude (L_s) is generally between 205 and 345 degrees. There are usually three distinct dust activities (A, B, and C) in the southern region during this period. The drag ΔV profiles during the past six high density seasons are shown in Figure 17. The three dust storms in 2014 are quite visible. Occasionally the dust activity could bloom into a global dust storm like in 2007. Navigation operations could see elevated atmospheric density scale factors during these times.

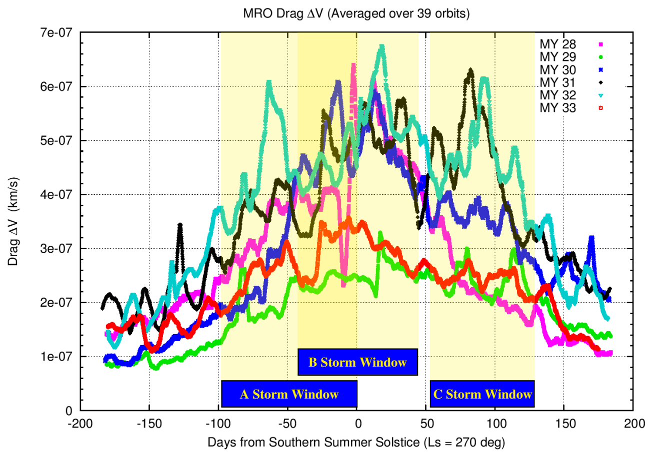

Fig. 17. MRO drag ΔV per orbit vs. days from Southern Summer Solstice.

Due to the increasingly crowded Martian environment potential collision with other orbiters is an ongoing concern. This has resulted in increased vigilance and an automated process is in place to assess any close approaches by other spacecraft to MRO. A process to take mitigative action if needed also exists.

7. Extended Mission Highlights

7.1. Mars Science Laboratory – August 2012

MRO successfully provided relay support via its UHF antenna during the EDL phase of MSL on August 6, 2012. This success required accurate phasing of MRO to the MSL relay target via the execution of two propulsive maneuvers designed by the MRO Navigation Team.[3] MRO's HiRISE camera also took a picture of the parachute landing of MSL (Figure 18).

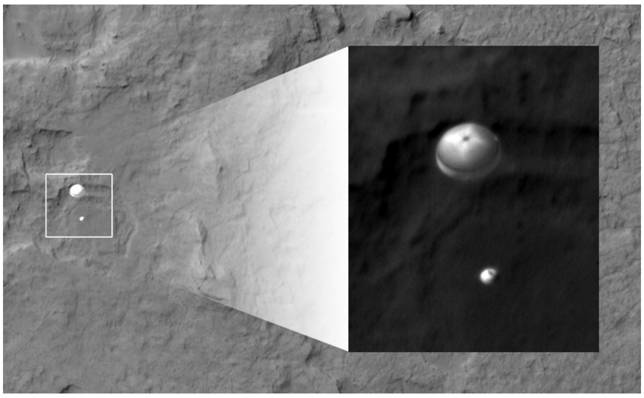

Fig. 18. Image of MSL parachute landing taken by HiRISE Camera. Source: NASA/JPL-Caltech.

7.2. Comet Siding Spring Flyby – October 2014

Comet Siding Spring encountered Mars on October 19, 2014 at a distance of about 140,500 km — the nearest comet flyby of a planet in recorded history. To help protect MRO from the incoming comet particles, the Navigation Team designed two propulsive maneuvers to position the spacecraft behind Mars at the arrival time of the expected peak particle fluency. The MRO Navigation Team also provided viewing periods with and without atmospheric occultation effects to aid the observations of the comet.[4] MRO was able to detect the comet, gather science data, and capture images of the comet as it approached Mars as seen in Figure 19.

7.3. ExoMars Schiaparelli Lander – October 2016

MRO planned to provide surface relay support for the brief mission of the ExoMars Schiaparelli lander on Mars in October 2016. To place MRO directly overhead on its third overflight of the Schiaparelli landing site, two propulsive maneuvers designed by the MRO Navigation Team were performed starting three months prior to Schiaparelli's arrival at Mars. This strategy allowed MRO to perform its overflight within about 10 seconds of the targeted time.[5] However, after an unsuccessful landing the plan to provide relay support to Schiaparelli was repurposed into acquiring pictures of the impact site using the CTX and HiRISE cameras.

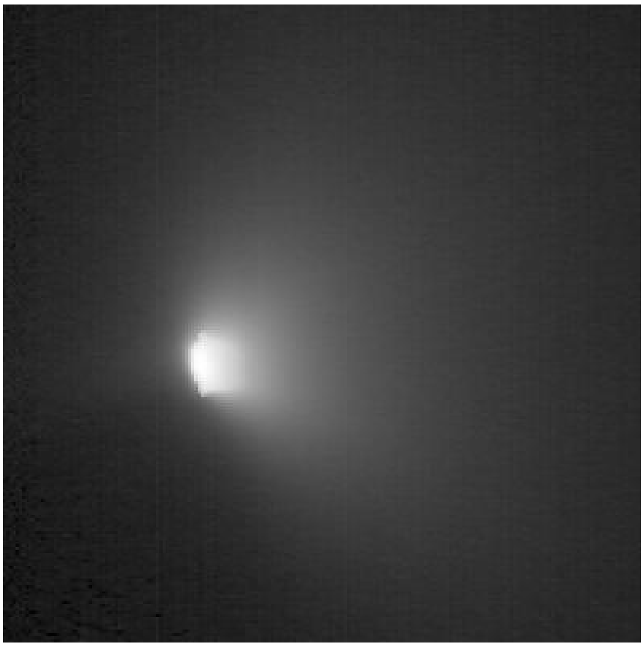

Fig. 19. Closest approach image of Comet Siding Spring taken by HiRISE Camera (nucleus saturated). *October 19, 2014 18:24 UTC at a range of 139,000 km, 28×28 km field-of-view. Source: Alan Delamere.*

Detailed images from the HiRISE camera revealed three separate locations showing the lander, the parachute, and the heat shield. With the HiRISE picture taken on November 1, 2016 (Figure 20), some of the bright spots around the impact area were confirmed to be material from Schiaparelli.

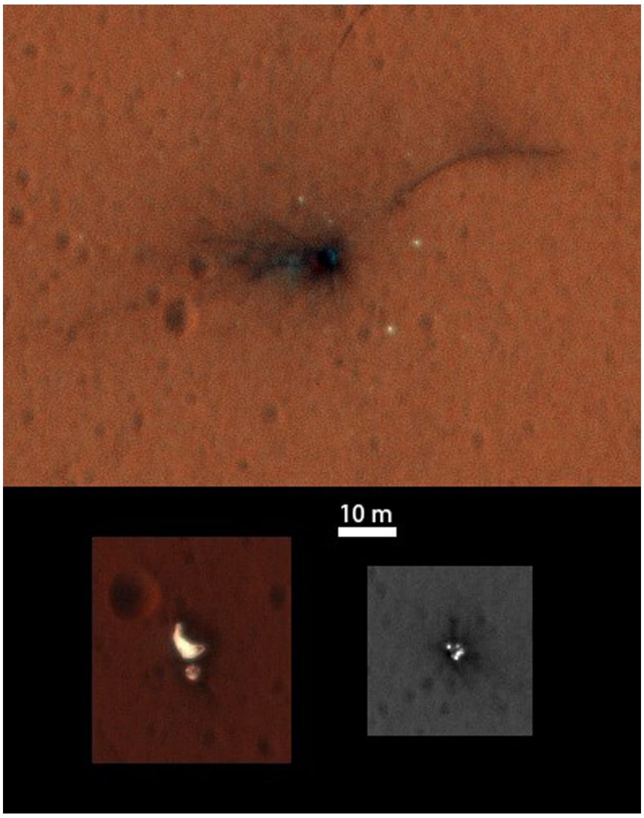

Fig. 20. Image of the Schiaparelli impact area taken by HiRISE on November 1, 2016. Source: NASA/JPL-Caltech.

7.4. Lunar Calibration – November 2016

On November 20, 2016, MRO was about 205 million km away when its HiRISE camera took two separate exposures of the Earth and Moon. Figure 21 shows a composite of both images, where Australia and Southeast Asia are the reddish areas in the middle and near the top of the Earth, respectively, and Antarctica is the bright spot on the bottom left. The images were taken to provide absolute radiometric calibration of HiRISE data.

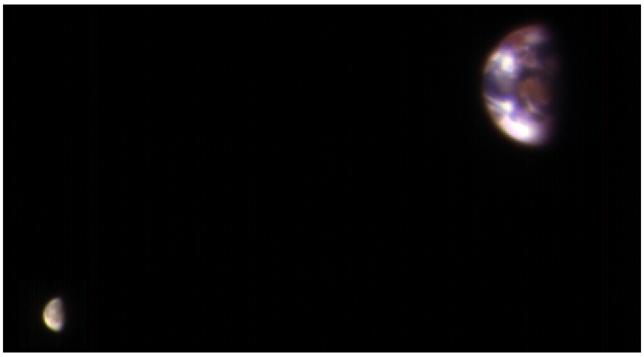

Fig. 21. Lunar calibration images of Earth and Moon taken by HiRISE Camera (IRB color). Source: NASA/JPL-Caltech.

8. Conclusion

The MRO Navigation Team successfully supported science operations and relay for landed missions at Mars for over 10 years. Navigation requirements have been consistently met through periodic trajectory prediction and reconstruction deliveries. Propulsive maneuvers performed since February 2007 were successful in controlling the GTW errors within mission requirements while maintaining the frozen condition of the science orbit. MRO also implemented maneuvers that satisfied LMST requirements for the PSO and the upcoming InSight mission, as well as phasing requirements for past missions such as the Phoenix lander, Mars Science Laboratory, and ExoMars Schiaparelli lander. As of March 31, 2017, MRO has a generous margin of about 206 kg of usable propellant, which translates to approximately 375 m/s of remaining ΔV. MRO will continue its science endeavors and relay support of landed assets at Mars, as well as provide relay support for future missions such as InSight and Mars 2020.

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. Reference to any specific commercial product, process, or service by trade name, trademark, manufacturer or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology. The authors thank Dan Johnston, Tomas Martin-Mur, and Tung-Han You for reviewing this paper. The authors also wish to acknowledge the past contributions of all previous members of the MRO Navigation Team.

References

1) You, T.-H., Halsell, A., Graat, E., Demcak, S., Highsmith, D., Long, S., Bhat, R., Mottinger, N., Higa, E., and Jah, M. "Navigating Mars Reconnaissance Orbiter: Launch Through Primary Science Orbit." AIAA SPACE 2007 Conference & Exposition, AIAA 2007-6093, September 18–20, 2007.
2) Highsmith, D., You, T.-H., Demcak, S., Graat, E., Higa, E., Long, S., Bhat, R., Mottinger, N., Halsell, A., and Peralta, F. "Mars Reconnaissance Orbiter Navigation During the Primary Science Phase." AIAA/AAS Astrodynamics Specialist Conference, AIAA 2008-6422, Honolulu, Hawaii, August 18–21, 2008.
3) Williams, J. L., Menon, P. R., and Demcak, S. W. "Mars Reconnaissance Orbiter Navigation Strategy for Mars Science Laboratory Entry, Descent and Landing Telecommunication Relay Support." AIAA/AAS Astrodynamics Specialist Conference, AIAA 2012-4747, Minneapolis, Minnesota, August 13–16, 2012.
4) Menon, P. R., Wagner, S. V., Martin-Mur, T. J., Jefferson, D. C., Ardalan, S. M., Chung, M.-K. J., Lee, K. J., and Schulze, W. B. "Mars Reconnaissance Orbiter Navigation Strategy for the Comet Siding Spring Encounter." AAS/AIAA Astrodynamics Specialist Conference, AAS 15-551, Vail, Colorado, August 9–13, 2015.
5) Menon, P. R., Wagner, S. V., Jefferson, D. C., Graat, E. J., Lee, K. J., and Schulze, W. B. "Mars Reconnaissance Orbiter Navigation Strategy for the ExoMars Schiaparelli EDM Lander Mission." AAS/AIAA Space Flight Mechanics Meeting, AAS 17-337, San Antonio, TX, February 5–9, 2017.
6) Wagner, S. V., Menon, P. R., Chung, M.-K. J., and Williams, J. L. "Mars Reconnaissance Orbiter Navigation Strategy for Dual Support of InSight and ExoMars Entry, Descent and Landing Demonstrator Module in 2016." AAS/AIAA Astrodynamics Specialist Conference, AAS 15-532, Vail, Colorado, August 9–13, 2015.
7) "Mars Reconnaissance Orbiter Navigation Plan." Tech. Rep. MRO-31-202, JPL D-22240, NASA Jet Propulsion Laboratory, Pasadena, CA, June 15, 2005.
8) Justus, C. G. "Mars Global Reference Atmospheric Model for Mission Planning and Analysis." Vol. 28, No. 2, pp. 216–221, 1990.
9) Evans, S., Taber, W., Drain, T., Smith, J., Wu, H.-C., Guevara, M., Sunseri, R., and Evans, J. "MONTE: The Next Generation of Mission Design & Navigation Software." International Conference on Astrodynamics Tools and Techniques, March 2016.
10) "NAIF - The Navigation and Ancillary Information Facility: The SPICE Toolkit." https://naif.jpl.nasa.gov/naif/toolkit.html.
11) Roundhill, I. and Kelly, R. M. "TARDIS: An Automation Framework for JPL Mission Design and Navigation." SpaceOps 2014 Conference, AIAA 2014-1726, Pasadena, CA, May 5–9, 2014.
12) Wagner, S. V., Menon, P. R., and Demcak, S. W. "Mars Reconnaissance Orbiter: Ten Years of Maneuver Support For Science Operations and Entry, Descent, and Landing Sequences." AAS/AIAA Space Flight Mechanics Meeting, AAS 17-287, San Antonio, TX, February 5–9, 2017.