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MARS RECONNAISSANCE ORBITER NAVIGATION STRATEGY FOR THE EXOMARS SCHIAPARELLI EDM LANDER MISSION

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The Mars Reconnaissance Orbiter (MRO) had planned to provide surface relay support for the brief mission of the ExoMars Schiaparelli EDM lander on Mars in October 2016. Launched with the Trace Gas Orbiter (TGO) in March 2016, Schiaparelli and TGO composed the first part of the ExoMars program. To place MRO directly overhead on its third overflight of the Schiaparelli landing site, two propulsive maneuvers were performed starting three months prior to Shiaparelli's arrival at Mars. This paper documents the maneuver strategy employed by the MRO Navigation Team to support the Schiaparelli overflight campaign.

INTRODUCTION

The Mars Reconnaissance Orbiter (MRO) spacecraft planned to provide primary relay support for the Entry, Descent, and Landing Demonstrator Module (EDM) during its brief surface mission. The EDM lander, better known as Schiaparelli, was scheduled to land on Mars on October 19, 2016. As part of the of the ExoMars program, a joint mission of the European Space Agency (ESA) and the Russian space agency Roscosmos, Schiaparelli was launched with ESA's Trace Gas Orbiter (TGO) on March 14, 2016. In the past MRO had supplied telecommunication relay support during the Entry, Descent, and Landing (EDL) sequences of two spacecraft: the Phoenix lander in May 2008[1] and Mars Science Laboratory (MSL) in August 2012.[2] However, MRO's support plan for the Schiaparelli lander did not include the EDL sequence. Instead, MRO was tasked only to support the overflights of the surface mission, with the third overflight optimized such that MRO would be directly overhead at its maximum elevation from the landing site. Two propulsive maneuvers were performed to place MRO at the requested EDM target time: the first maneuver three months prior to landing in order to remove most of the predicted timing offset of 31 minutes and the second maneuver one month prior to landing for correcting the remaining phasing offset. This strategy allowed MRO to perform its overflight within about 10 seconds of the targeted time. The offset with respect to the trajectory information uploaded to EDM lander 16 days prior to landing was smaller — about 4 seconds. Although Schiaparelli's soft landing attempt did not succeed, MRO was still able to provide ESA with valuable images during its overflights over the impact site. This paper documents the implemented maneuver plan by the MRO Navigation Team to support the Schiaparelli overflight campaign.

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MRO PRIMARY SCIENCE ORBIT

The Primary Science Orbit (PSO) for MRO operations is a 252 km $\times$ 317 km altitude, sun-synchronous orbit with the periapsis frozen over the south pole and the ascending node at 3:00 PM. The mean orbital elements are shown in Table 1. The orbit is designed to exactly repeat after 4602 revolutions in 349 sols (1 sol = 1.0275 days), with separation between ground tracks of less than 5 km at the equator. The near-repeat cycle used for science planning is a 211-orbit cycle (16 sols) that walks about 0.5 deg (32.5 km) in longitude westward from the previous cycle. The orbit maintenance is done based on this near repeat cycle.

Table 1: MRO Mean Orbital Elements

Periapsis Epoch: 20-Oct-2016 16:50:39.228 ET	
Semi-Major Axis (a)	3648.9679 km
Eccentricity (e)	0.0051
Inclination (i)	92.6524°
Argument of Periapsis (ω)	270.1373°
Right Ascension of Node (Ω)	151.9305°
True Anomaly (v)	0.0°
Additional Orbit Information	
Apoapsis Epoch: 20-Oct-2016 17:46:59.958 ET	
Period (T)	111.54 min
Periapsis Altitude (H_p)	254.0857 km
Apoapsis Altitude (H_a)	316.1615 km

SCHIAPARELLI MISSION OVERVIEW

The Schiaparelli lander was intended to test technology for future landings on Mars. The lander also included a science payload that would have measured atmospheric electricity on Mars and local meteorological conditions. As part of the ExoMars program, Schiaparelli was launched with the Trace Gas Orbiter (TGO) on March 14, 2016. After completing a seven-month cruise to Mars, TGO and Schiaparelli separated on October 16, 2016. Three days later TGO was inserted into a Mars orbit via a two-hour long engine burn while Schiaparelli attempted a soft landing by slowing its descent utilizing a heat shield, parachute and retrorockets. Unfortunately, the EDL sequence did not execute as planned. Telemetry signals from Schiaparelli were lost just prior to the predicted landing time. The engineering data collected briefly from Schiaparelli by TGO during the descent phase could be analyzed to assist future landing attempts. Currently, TGO is in its planned initial Mars orbit. Following a series of maneuvers to aero-brake during early 2017, it plans to begin its primary science mission in late 2017. This orbiter is also expected to provide relay support for the ExoMars 2020 rover and other landed assets.[3]

SELECTION PROCESS FOR SCHIAPARELLI OVERFLIGHT TARGET

MRO had been identified as the prime relay service provider for the Schiaparelli lander. It was expected to provide support for up to 14 sols after EDL, which would aid the UHF and data flow performance analysis. This level of support included enabling successful forward- and return-link data transfers to Schiaparelli. The MRO project had agreed to maintain MRO's orbit for the relay support for at least the first four sols (prime support period) of the Schiaparelli surface mission.[4] MRO's support focus on the front end of the 14-day relay period was partly due to Schiaparelli's expected battery life. The European Space Operations Center - Flight Dynamics (ESOC-FD) Team provided a technical note to the MRO project defining the required target orbit phase for MRO. The MRO phase control corridor with respect to the target phase was defined as $\pm$5 minutes.[5] The following requirements were used by ESOC-FD to derive the requested MRO relay target (see Reference 5):

1. EDL relay is outside the scope of the MRO support.
2. MRO shall support the first post-EDL relay session.

3. The first pass after landing is desired to occur within 3 hours after landing.
4. MRO shall have good overflight pass geometry within the first 2 Sols after landing. A good overflight pass geometry is characterized by:
   (a) The pass duration (defined from horizon to horizon) is longer than 10 min.
   (b) The maximum elevation of the pass is higher than 30 deg.
5. There are no requirements on the relative slant range, range-rate and range-rate-rate.
6. There are no requirements for the overflight to occur at a defined local time (in particular local day or night).

A visibility analysis was performed by the ESOC-ED based on MRO's orbit and the nominal EDM landing coordinates. MRO Navigation also independently verified this visibility analysis (see Appendix A). Based on the aforementioned requirements, the phasing target was chosen while taking into account the MRO phasing control corridor and favoring a better overflight geometry. This selection process optimized the geometry of the third overflight such that the maximum elevation of the pass was the largest as compared to the other passes through the fifth overflight. The support agreement between JPL and ESA had originally specified the optimization of the first overflight, but was later revised to reflect the change to the third overflight as the requested target.

The EDL Relay Target File (ERTF) which ESOC-FD provided to the MRO Navigation Team for the final phasing maneuver design (see Figure 1) contained the requested relay target, as well as the predicted entry and landing epochs and coordinates. This requested relay target for MRO to achieve with the final planned phasing maneuver corresponds to the time of the maximum elevation during the third overflight pass after landing. Table 6 in Appendix B presents the ERTF delivery history.

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-----------------------------------------------------------------------------------------------
EDL RELAY TARGETS FILE (ERTF)
-----------------------------------------------------------------------------------------------

Data generated on 05 September 2016

ERTF Version: 08

MRO OEM File: ooem_mro_20161019-20161104_20160830traj.txt


**************************************************************
*   MRO RELAY TARGETS (2000 IAU Mars Fixed)
*   Epoch              : 2016/10/20 17:17:43.789 ET
*   Latitude           : -2.05 deg
**************************************************************


EDM Data (2000 IAU Mars Fixed)
Entry Epoch               : 2016/10/19 14:43:17.082 ET
     Entry Latitude       : -3.6234 deg
     Entry Longitude      : 342.6699 deg
Landing Epoch             : 2016/10/19 14:48:51.397 ET
     Landing Latitude     :-2.0500 deg
     Landing Longitude    : 353.9000 deg
     Landing Radius       : 3394.071 km
```

Figure 1: EDL Relay Target File Used for Final Phasing Maneuver (ERTF-08)

SCHIAPARELLI OPTIMAL OVERFLIGHT PHASING STRATEGY

The MRO Navigation Team developed a maneuver plan for phasing MRO to the overflight target requested by ESA. The maneuver strategy was especially designed to mitigate uncertainties due to atmospheric drag and other orbital effects. A two-maneuver phasing approach was implemented for correcting the timing offset while minimizing the chance of overshooting the phasing target. Just prior to the first maneuver, the predicted phasing offset from the Schiaparelli's target was about 31 minutes (early), or approximately one-quarter of MRO's orbital period (∼112 minutes). Two in-plane Orbit Trim Maneuvers (OTMs) would impart ΔV in the pro-velocity direction to slow down MRO so that it would reach the target within the ±5 minutes phasing requirement (see Reference 5).

Anticipated Atmospheric Drag and Navigation Timing Uncertainties

The atmospheric density variation is the largest contributor to errors in the MRO navigation accuracy, barring a significant maneuver execution error.[6] As shown in Figure 2, the atmospheric drag was anticipated to be much higher leading up to the Schiaparelli landing than when phasing was performed to support the EDL sequences of the Phoenix and MSL missions and the risk mitigation efforts with the Comet Siding Spring flyby of Mars;[7] maneuver planning was done assuming a drag ΔV of 0.4 mm/s per orbit. Consequently, the expected navigation timing uncertainties (Figure 3) were significantly larger than at previous EDL support periods. Correcting the phasing only up to the navigation uncertainty level at a given maneuver opportunity would avoid potentially overshooting the target time. When planning the phasing strategy it was also recognized that the maneuver ΔV should not go below the minimum control capability of 20 mm/s.

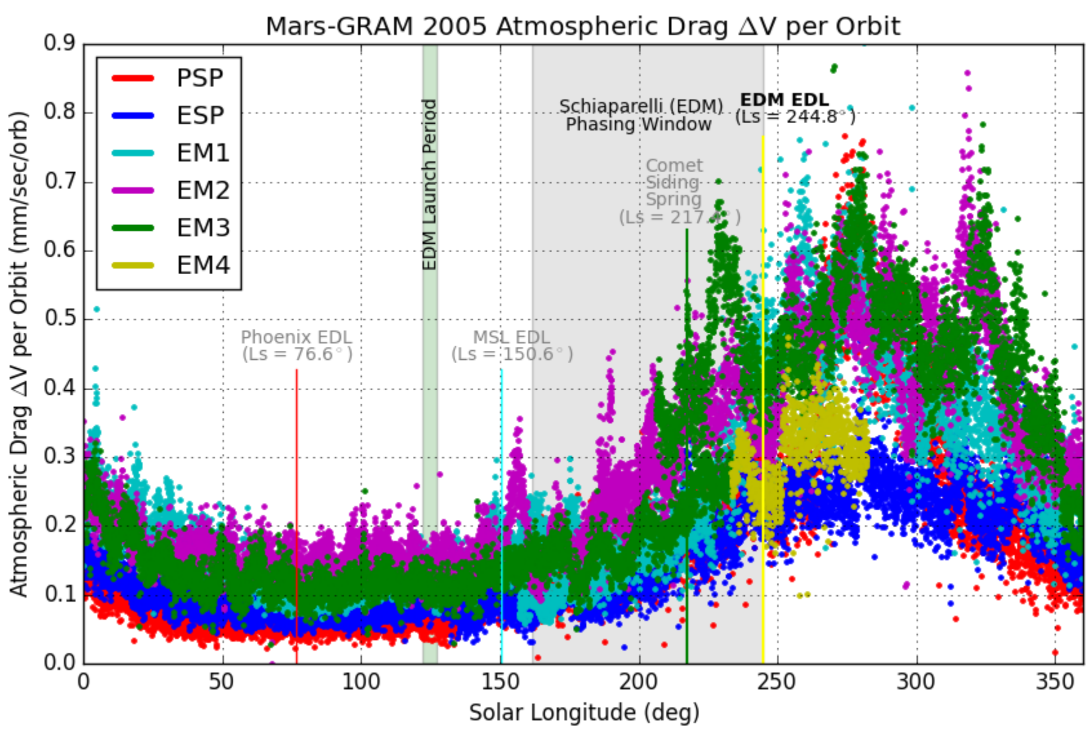


Figure 2: Atmospheric Drag ΔV Experienced by MRO through December 2016. *Color-coded by mission phase: PSP = Primary Science Phase, ESP = Extended Science Phase, EM = Extended Mission (1-4)*

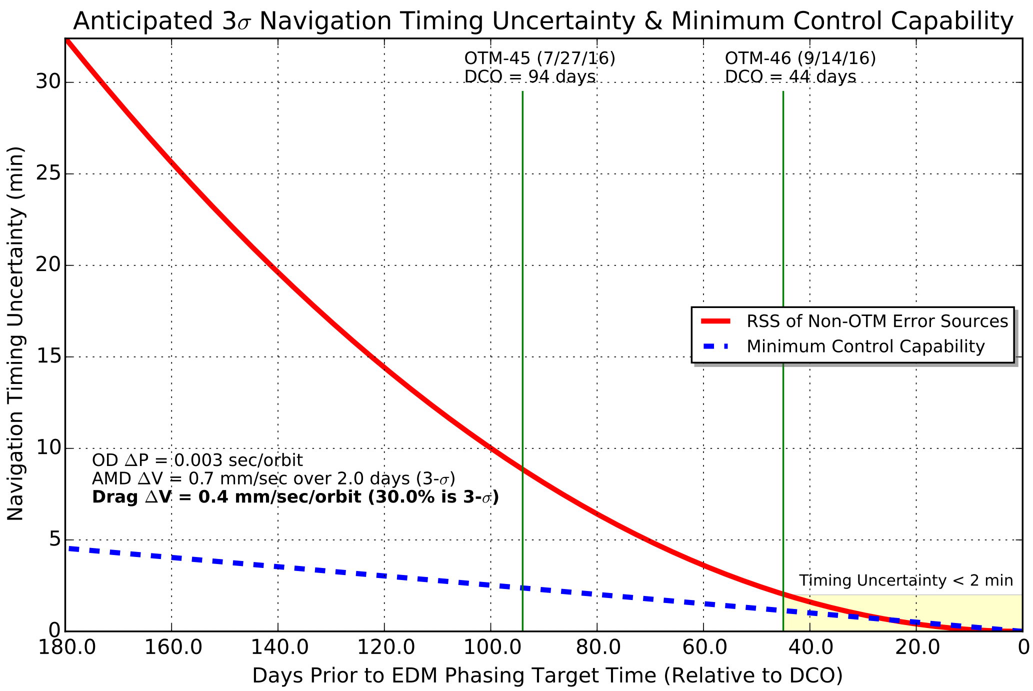


Figure 3: MRO Navigation Timing Uncertainty (3-σ) Prior to Schiaparelli Overflight Target Time

Phasing Maneuvers (OTM-45 and OTM-46)

Orbit phasing is accomplished via in-plane OTMs, also referred to as Orbit Synchronization Maneuvers (OSMs). OTM-45 (OSM-1), the first of two pro-velocity OSMs, was executed on July 27, 2016, about three months prior to the Schiaparelli landing. When the maneuver strategy was initially planned, the predicted phasing offset from the target time defined by ERTF-01 (see Table 6 in Appendix B) was about 39 minutes early. However, at the time of the final maneuver design (one week prior to the OTM-45 execution) as the orbit determination evolved the phasing offset naturally drifted to 31 minutes early. Limiting the phasing correction to the navigation uncertainty (8.9 minutes) at the OTM-45 data cut-off (DCO) of 94 days from the Schiaparelli overflight target time (Figure 3), OTM-45 was designed to remove about 21 minutes of phasing offset. This maneuver performed nominally with only a slight overburn of 2%. Table 2 lists the estimated phasing errors at the EDM target prior to and following each phasing maneuver, as well as the expected down-track timing uncertainties at each maneuver opportunity. Targets given in ERTF-04 and ERTF-08 were used to design OTM-45 and OTM-46, respectively.

Table 2: History of Phasing Offset from Schiaparelli Overflight Target Time

	OTM-45 (OSM-1)	OTM-46 (OSM-2)	OTM-46 Backup	EDM Overflight Target
OSM Date	7/27/2016	9/14/2016	9/21/2016	10/20/2016
Days OSM Prior to EDM Target	85	36	29	
OSM ΔV (Designed)	0.1884 m/s	0.2066 m/s	*cancelled*	
Target File	ERTF-04	ERTF-08		ERTF-08
EDM Phasing Offset (Pre-OSM)	30.6 min early	9.6 min early		
EDM Phasing Offset (Post-OSM)	9.5 min early	2.5 sec late		**10.4 sec late**
EDM Phasing Correction via OSM	**20.6 min early**	**9.6 min early**		**(reconstructed)**
Down-Track Timing Uncertainty (3-σ)	8.9 min	2.0 min	1.5 min	
OD DCO for OSM	7/18/2016	9/6/2016	9/12/2016	
Days DCO Prior to EDM Target	94	44	38	

After completion of OTM-45 a timing offset of about 10 minutes remained. This was to be corrected via OTM-46 (OSM-2), the second planned OSM, on September 14, 2016. This maneuver also performed quite well (1.7% overburn) placing MRO late by only 2.5 seconds from the target time. This was within the down-track timing uncertainty of 2 minutes (44 days prior to EDM EDL). The MRO trajectory reconstruction done following the Schiaparelli landing indicated that the spacecraft was actually late at the target location by about 10.4 seconds. As expected, the atmospheric density variations, etc., contributed to this slight change in the phasing offset. A summary of the design and reconstructed ΔVs of the two phasing maneuvers (OTM-45 and OTM-46) and the post-EDM EDL PSO recovery maneuver (OTM-47) discussed in a later section is given in Table 3.

Table 3: MRO Maneuver History for Schiaparelli Overflight Phasing and PSO Recovery

Maneuver	Maneuver Epoch (UTC SCET)	Orbital Apsis/ Node	Data Source	ΔV (mm/s)		Right Ascension (deg)		Declination (deg)		Duration (sec)	
				Value	$\|err\|$	Value	$\|err\|$	Value	$\|err\|$	Dur	$\|err\|$
OTM-45	27-Jul-2016 12:33:57	Peri	Recon	192.1	3.7	158.54	0.08	36.73	0.01	8.8	0.1
			Design	188.4		158.63		36.72		8.7	
OTM-46	14-Sep-2016 12:57:13	Peri	Recon	210.2	3.6	186.37	0.06	25.45	0.01	9.4	0.0
			Design	206.6		186.43		25.44		9.4	
OTM-46 (backup)	21-Sep-2016 13:16:14	Peri	*. . . . Contingency maneuver if OTM-46 on 14-Sep-2016 did not execute . . . .*								
			Design	257.2		190.28		24.16		11.9	
Schiaparelli Overflight Target Time (Third Overflight): 20-OCT-2016 17:17:43.7890 ET SCET											
OTM-47	02-Nov-2016 12:29:27	Apo	Recon	224.1	4.7	30.69	0.10	-13.25	0.00	9.9	0.1
			Design	219.4		30.79		-13.25		10.0	

Atmospheric drag reduces the energy of MRO in its orbit, which decreases the orbital period and increases the ground track walk (GTW) error. Pro-velocity maneuvers increase the semi-major axis, thus extending the orbital period. Thus this maneuver approach also aided the GTW control error limited only by the phasing required by Schiaparelli (see Figure 4). Reference 8 provides a more detailed discussion of the GTW maintenance strategy employed by MRO.

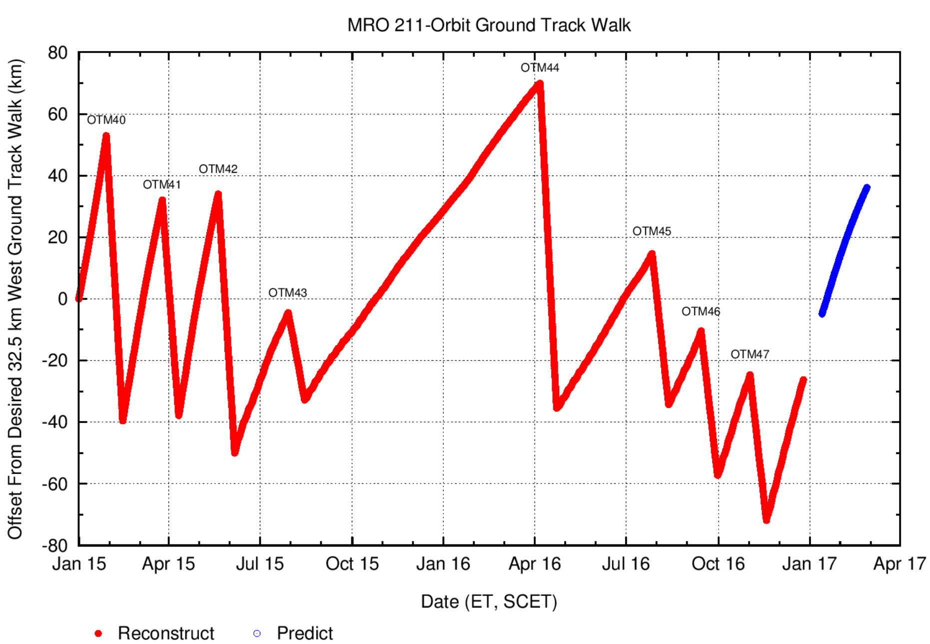


Figure 4: MRO Orbit Ground Track Walk Repeat Error from January 2015 – April 2017

Phasing Offset Evolution History

The MRO Navigation Team had started tracking the Schiaparelli phasing offset after the completion of OTM-44 on April 6, 2016 and well before the first phasing maneuver (OTM-45). The atmospheric density variations and other orbit determination inaccuracies were expected to affect the phasing offset. As the orbit determination of MRO is done at least twice per week, it was possible to periodically assess the current offset from the final desired target time. These offsets were reported to the MRO project weekly. The phasing offset values and associated navigation errors are given in Figure 5. A negative sign in the offset indicates being late and a positive sign indicates being early. For example, prior to the second phasing maneuver OTM-46, MRO was expected to arrive earlier at the desired target phase, while after the maneuver it was to arrive slightly late. Also shown in Figure 5 are the different Density Scale Factors (DSFs) used in propagating the trajectory to estimate phasing offsets. The DSF adjusts the Mars-GRAM atmospheric model used for prediction. Beginning on June 26, 2016 the solar arrays were in fixed configuration helping to extend the gimbal life. This in turn reduced the effective area subjected to atmospheric drag, returning the phasing offsets to near expected levels. Following OTM-45 the Martian atmosphere remained fairly stable, so the predicted DSF and phasing offset also remained stable. A dust storm started on September 5, 2016 and lasted till October 10, 2016. Even though the dust activity resulted in changes in the DSF there was not enough propagation time to make any significant impact to the phasing offset.

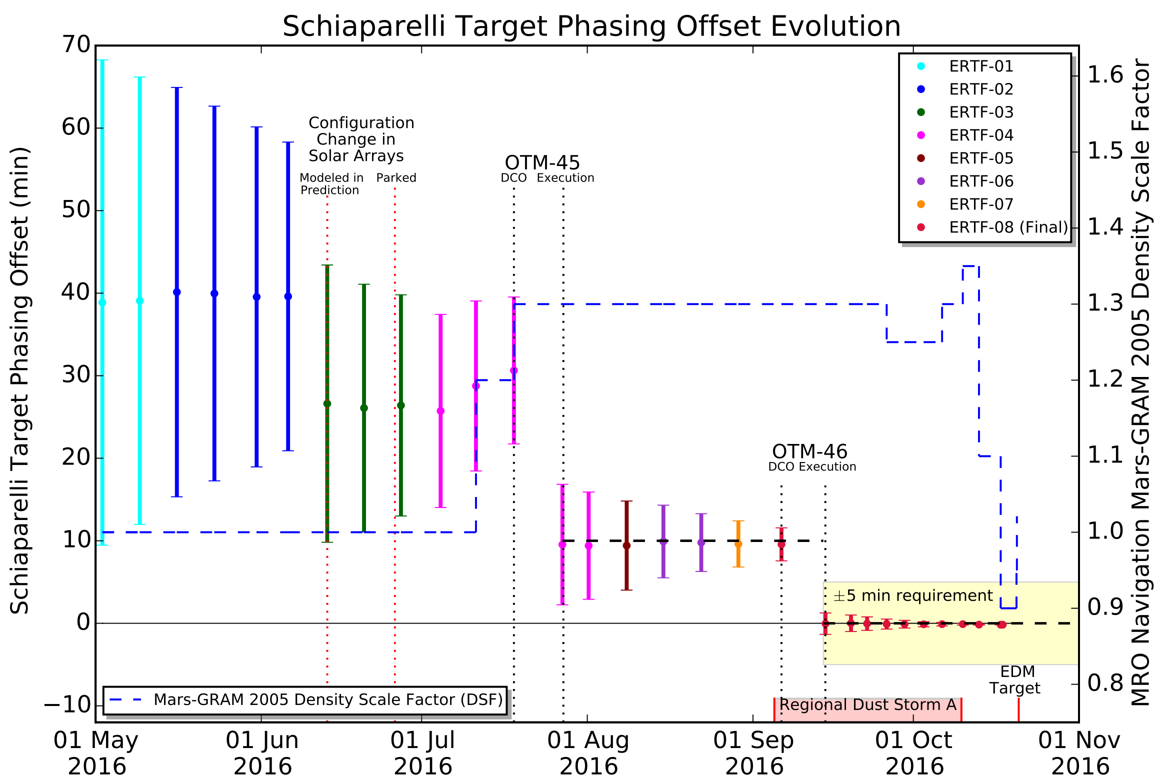


Figure 5: Evolution of the Schiaparelli Target Phasing Offset. *Color-coding is used to match computed phasing offsets with specific ERTFs.*

Table 4 gives the phasing offset values as computed with each orbit solution used for prediction every Monday and then nearly daily in the final week leading to Schiaparelli's arrival at Mars. The 3-σ navigation timing uncertainty value for each phasing offset entry is also provided. The first column in the table lists the ERTF version numbers, color-coded to match the phasing offset bars plotted in Figure 5. Also shown in the table are the data cut-off in days used in the orbit determination and the days to the Schiaparelli overflight time. The OTM-45 design purposely excluded the remaining 10 minutes of the predicted phasing offset. This was based on the 8.9 minutes timing uncertainty at the time of the maneuver design. The final reconstructed timing offset value of −10.4 sec is highlighted in yellow in the table.

In addition to designing maneuvers to achieve the desired phasing conditions, the MRO Navigation Team was tasked to perform accurate orbit determination (OD) for the predicted trajectory to be provided to ESA for uplinking to Schiaparelli. This information once onboard the lander was to aid in linking with the MRO orbiter and transmit data as the spacecraft rose in the martian horizon. The trajectory file based on an orbit solution generated on September 26, 2016 for MRO operations was given to ESA. This information was uplinked to Schiaparelli while in flight on October 3, 2016 well before its separation from TGO. The Navigation team also tracked the performance of this trajectory as shown in Table 4, last column. Schiaparelli had planned to transmit about 10 minutes before MRO rise and continue till 10 minutes after its set. If Schiaparelli had a nominal landing, MRO would have risen only about 4 seconds later than the expected rise time. To be better prepared, a successful interface test was conducted with a routine OD by the MRO Navigation Team to support MRO project operations on June 6, 2016. This trajectory file was provided to ESA and JPL teams.

Table 4: Evolution of the Schiaparelli Overflight Phasing Offset (Selected Values)

ERTF	OD Data Cut-off	Days to EDM Target	EDM Phasing Offset + (early) − (late)	3σ Nav. Timing Unc.	ERTF	OD Data Cut-off	Days to EDM Target	EDM Phasing Offset + (early) − (late)	3σ Nav. Timing Unc.	1st Overflight vs. Onboard EDM Timing (Sep 26, 2016)
01	May 2, 2016	171	+38.9 min	29.4 min	07	Aug 29, 2016	52	+9.6 min	2.8 min	
01	May 9, 2016	164	+39.1 min	27.1 min	08	Sep 6, 2016	44	+9.6 min	2.0 min	
02	May 16, 2016	157	+40.1 min	24.8 min	OTM-46 (September 14, 2016)					
02	May 23, 2016	150	+40.0 min	22.7 min	08	**Sep 14, 2016**	**36**	**−2.52 sec**	**1.3 min**	
02	May 31, 2016	143	+39.6 min	20.6 min	08	Sep 19, 2016	31	+0.21 sec	1.0 min	
02	June 6, 2016	136	+39.6 min	18.7 min	08	Sep 22, 2016	28	−2.29 sec	49 sec	
03	June 13, 2016	129	+26.6 min	16.8 min	08	Sep 26, 2016	24	−5.63 sec	36 sec	
03	June 20, 2016	122	+26.1 min	15.0 min	08	Sep 29, 2016	21	−6.57 sec	28 sec	−0.87 sec
03	June 27, 2016	115	+26.4 min	13.4 min	08	Oct 3, 2016	17	−6.99 sec	19 sec	−1.26 sec
04	July 4, 2016	108	+25.7 min	11.7 min	08	Oct 6, 2016	14	−6.15 sec	13 sec	−0.57 sec
04	July 11, 2016	101	+28.8 min	10.3 min	08	Oct 10, 2016	10	−6.20 sec	7 sec	−0.68 sec
04	July 18, 2016	94	+30.6 min	8.9 min	08	Oct 13, 2016	7	−9.58 sec	3 sec	−3.44 sec
OTM-45 (July 27, 2016)					08	Oct 17, 2016	3	−10.41 sec	1 sec	−4.03 sec
04	**July 27, 2016**	**85**	**+9.5 min**	**7.3 min**	08	Oct 18, 2016	3	−10.40 sec	1 sec	−4.01 sec
04	Aug 1, 2016	80	+9.4 min	6.5 min	08	Oct 19, 2016	2	−10.40 sec	0.3 sec	−4.01 sec
05	Aug 8, 2016	73	+9.4 min	5.4 min	08	Oct 20, 2016	0	−10.37 sec	0.02 sec	–
06	Aug 15, 2016	66	+9.9 min	4.4 min	EDM 3rd Overflight Target (October 20, 2016)					
06	Aug 22, 2016	59	+9.8 min	3.5 min	08	**Reconstruction**		**−10.40 sec**	**–**	**−4.02 sec**

SCHIAPARELLI LANDING

Unfortunately, the Schiaparelli lander did not survive its Martian descent on October 19, 2016. The expected times of entry and touch down were 14:43:17 ET and 14:48:57 ET respectively. Even though the drag ΔV was expected to be higher than at previous relay support periods, it did not rise to the anticipated high levels as seen in Figure 6. This lower-than-expected drag ΔV was probably due to the decreased solar activity. The drag ΔV averaged over 39 orbits over the Schiaparelli EDL period is shown in cyan in Figure 6. For comparison, the drag ΔV during a similar time frame in the previous Mars year is indicated in blue. Also shown in red and pink are the periods of southern polar dust events. Prior to the Schiaparelli landing phase, the southern polar dust event-A started on September 5, 2016 lasting until October 10, 2016.

Following the Schiaparelli EDL time frame, OTM-47 was used to re-establish the PSO to resume normal science operations. This was again a pro-velocity maneuver countering the drag effects. A southern polar dust event-B began on November 17, 2016 with the atmospheric density levels dropping soon after November 28 at summer southern solstice (solar longitude = 270°).

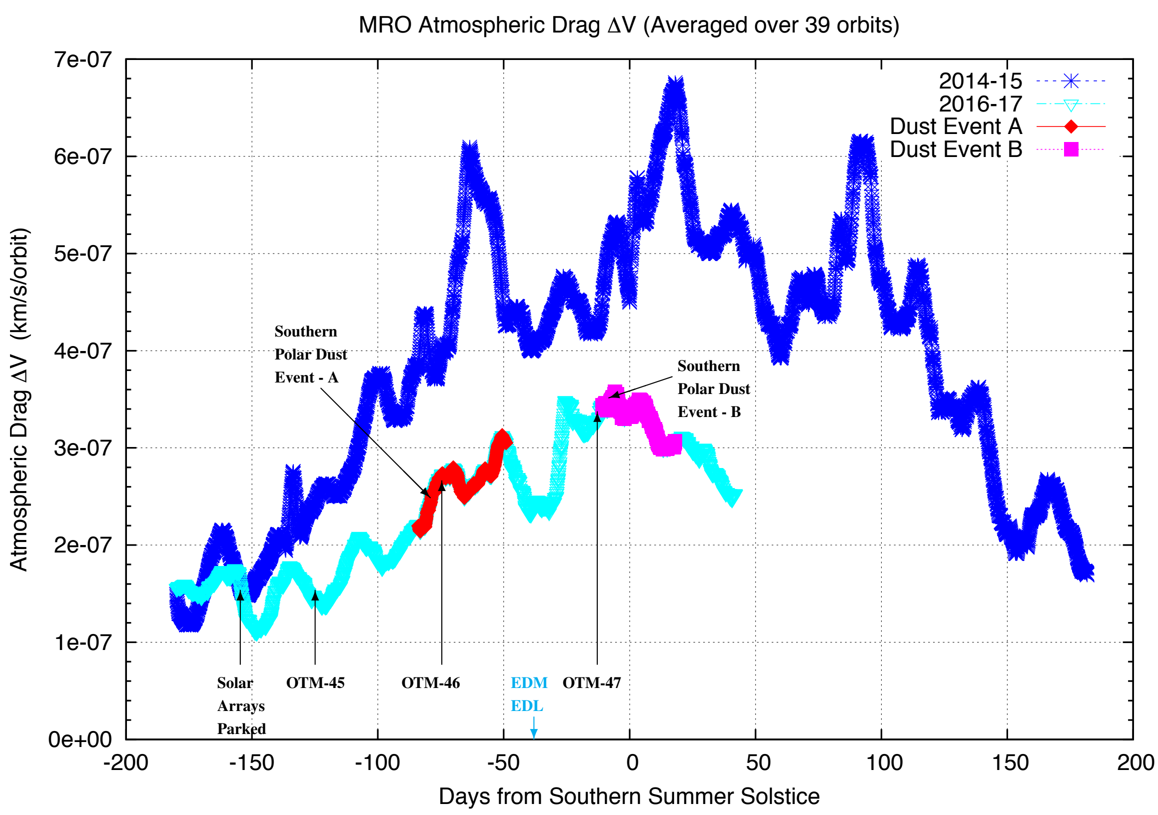


Figure 6: MRO Drag ΔV Per Orbit. *Days from Southern Summer Solstice (Day 0: November 28, 2016)*

Planned Schiaparelli Overflights

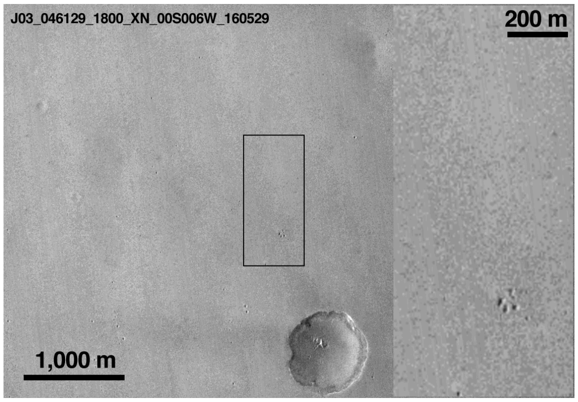
The MRO project was expected to supply low-latency support for up to 14 sols after Schiaparelli EDL. This support was needed for the UHF and data flow performance analysis. This would have covered the prime support period which was the first four sols of the Schiaparelli surface mission.[4] Table 5 shows the Schiaparelli overflight profile in the first 14 days following landing. Overflights with pass durations of at least 10 minutes and maximum elevation angles of at least 30 degrees are highlighted in yellow, with the optimized third overflight highlighted in green.

Table 5: Predicted Schiaparelli Overflights in First 14 Days

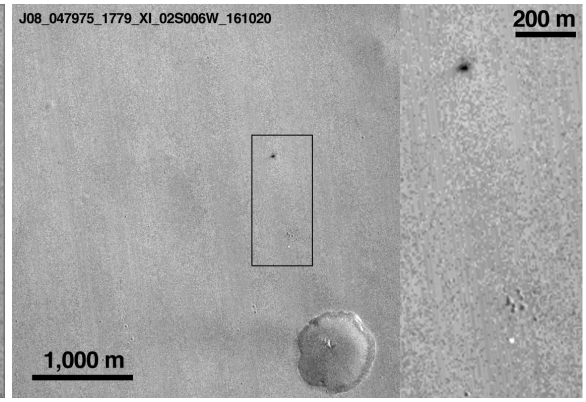
#	Pass Start (relative to EDM Landing)	Pass Start Time (ET)	Pass Length (min)	Max Elevation Angle (deg)	Max Elevation Time (ET)	MRO Off-Nadir Angle (deg)	Day/Night Pass
0	0.3 hrs (0.01 days)	19-OCT-2016 15:07:02.6592	1.55	0.06	19-OCT-2016 15:07:54.6094	67.88	Day
1	2.1 hrs (0.09 days)	19-OCT-2016 16:52:25.3249	13.31	38.17	19-OCT-2016 16:58:56.4147	-46.88	Day
2	14.2 hrs (0.59 days)	20-OCT-2016 05:03:21.6560	13.55	51.99	20-OCT-2016 05:10:17.7994	34.95	Night
3	26.4 hrs (1.10 days)	20-OCT-2016 17:11:12.4494	13.67	89.46	20-OCT-2016 17:17:53.4724	-0.57	Day
4	38.6 hrs (1.61 days)	21-OCT-2016 05:22:16.7167	13.64	66.67	21-OCT-2016 05:29:16.1636	-21.48	Night
5	50.7 hrs (2.11 days)	21-OCT-2016 17:30:20.6250	13.34	38.63	21-OCT-2016 17:36:53.2419	46.40	Day
6	62.9 hrs (2.62 days)	22-OCT-2016 05:41:35.6277	13.04	29.11	22-OCT-2016 05:48:16.3403	-54.01	Night
7	64.8 hrs (2.70 days)	22-OCT-2016 07:36:32.9001	5.66	2.01	22-OCT-2016 07:39:24.1843	67.79	Night
8	75.0 hrs (3.13 days)	22-OCT-2016 17:49:54.7561	12.28	18.51	22-OCT-2016 17:55:58.6994	61.49	Day
9	76.9 hrs (3.20 days)	22-OCT-2016 19:42:55.0406	8.71	5.62	22-OCT-2016 19:47:14.1629	-67.29	Day
10	87.2 hrs (3.63 days)	23-OCT-2016 06:01:23.2127	11.60	14.16	23-OCT-2016 06:07:19.6008	-63.93	Night
11	89.1 hrs (3.71 days)	23-OCT-2016 07:53:25.4505	10.05	8.35	23-OCT-2016 07:58:31.0760	66.49	Night
12	99.4 hrs (4.14 days)	23-OCT-2016 18:10:00.9433	10.20	8.63	23-OCT-2016 18:15:06.8476	66.34	Day
13	101.2 hrs (4.22 days)	23-OCT-2016 20:00:37.8498	11.48	13.70	23-OCT-2016 20:06:17.3156	-64.25	Day
14	111.5 hrs (4.65 days)	24-OCT-2016 06:21:48.3036	8.93	5.88	24-OCT-2016 06:26:22.7064	-67.19	Night
15	113.4 hrs (4.72 days)	24-OCT-2016 08:11:22.9050	12.20	17.97	24-OCT-2016 08:17:35.7764	61.91	Night
16	123.7 hrs (5.15 days)	24-OCT-2016 18:31:07.4170	6.01	2.17	24-OCT-2016 18:34:11.4085	67.78	Day
17	125.5 hrs (5.23 days)	24-OCT-2016 20:18:54.2098	12.97	28.10	24-OCT-2016 20:25:15.6584	-54.91	Day
18	135.9 hrs (5.66 days)	25-OCT-2016 06:44:21.8727	1.87	0.10	25-OCT-2016 06:45:22.8814	-67.94	Night
19	137.7 hrs (5.74 days)	25-OCT-2016 08:29:47.0290	13.32	37.31	25-OCT-2016 08:36:35.6266	47.63	Night
20	149.8 hrs (6.24 days)	25-OCT-2016 20:37:31.9337	13.61	63.90	25-OCT-2016 20:44:11.2394	-24.17	Day
21	162.0 hrs (6.75 days)	26-OCT-2016 08:48:32.3366	13.68	87.34	26-OCT-2016 08:55:32.9375	2.55	Night
22	174.1 hrs (7.26 days)	26-OCT-2016 20:56:29.8766	13.55	54.00	26-OCT-2016 21:03:08.0317	33.02	Day
23	186.3 hrs (7.76 days)	27-OCT-2016 09:07:39.7022	13.36	39.59	27-OCT-2016 09:14:30.4172	-45.54	Night
24	198.5 hrs (8.27 days)	27-OCT-2016 21:15:51.5536	12.80	24.49	27-OCT-2016 21:22:09.5720	57.51	Day
25	200.4 hrs (8.35 days)	27-OCT-2016 23:09:59.2935	6.93	3.17	27-OCT-2016 23:13:25.8175	-67.75	Day
26	210.6 hrs (8.78 days)	28-OCT-2016 09:27:13.9030	12.28	18.81	28-OCT-2016 09:33:31.0671	-61.26	Night
27	212.5 hrs (8.86 days)	28-OCT-2016 11:20:16.1139	8.74	5.59	28-OCT-2016 11:24:41.0426	67.25	Night
28	222.8 hrs (9.28 days)	28-OCT-2016 21:35:42.6443	11.18	11.93	28-OCT-2016 21:41:15.9593	65.03	Day
29	224.6 hrs (9.36 days)	28-OCT-2016 23:27:14.7690	10.59	10.08	28-OCT-2016 23:32:28.4860	-65.87	Day
30	235.0 hrs (9.79 days)	29-OCT-2016 09:47:20.7042	10.18	8.70	29-OCT-2016 09:52:33.1587	-66.34	Night
31	236.8 hrs (9.87 days)	29-OCT-2016 11:37:55.0142	11.50	13.55	29-OCT-2016 11:43:45.6705	64.34	Night
32	247.1 hrs (10.30 days)	29-OCT-2016 21:56:15.5601	8.10	4.47	29-OCT-2016 22:00:20.5561	67.45	Day
33	248.9 hrs (10.37 days)	29-OCT-2016 23:45:18.9394	12.50	21.17	29-OCT-2016 23:51:27.2058	-59.84	Day
34	259.3 hrs (10.81 days)	30-OCT-2016 10:08:27.3998	5.99	2.17	30-OCT-2016 10:11:32.6011	-67.84	Night
35	261.1 hrs (10.88 days)	30-OCT-2016 11:56:08.2932	12.97	27.66	30-OCT-2016 12:02:45.7482	55.28	Night
36	273.2 hrs (11.39 days)	31-OCT-2016 00:03:47.0592	13.45	45.39	31-OCT-2016 00:10:21.8133	-40.70	Day
37	285.4 hrs (11.89 days)	31-OCT-2016 12:14:43.6943	13.62	62.60	31-OCT-2016 12:21:42.0387	25.38	Night
38	297.6 hrs (12.40 days)	01-NOV-2016 00:22:34.9437	13.66	76.15	01-NOV-2016 00:29:15.7291	12.79	Day
39	309.7 hrs (12.91 days)	01-NOV-2016 12:33:39.8070	13.56	55.09	01-NOV-2016 12:40:36.7946	-32.00	Night
40	321.9 hrs (13.41 days)	02-NOV-2016 00:41:44.4830	13.18	32.61	02-NOV-2016 00:48:12.7457	51.34	Day
41	323.8 hrs (13.49 days)	02-NOV-2016 02:37:25.0021	4.15	1.02	02-NOV-2016 02:39:28.9836	-67.94	Day
42	334.1 hrs (13.92 days)	02-NOV-2016 12:53:00.4167	12.81	24.83	02-NOV-2016 12:59:33.7942	-57.19	Night
43	336.0 hrs (14.00 days)	02-NOV-2016 14:47:11.7082	7.01	3.22	02-NOV-2016 14:50:43.2759	67.66	Night

Schiaparelli Impact Area

After the unsuccessful landing, the plan to provide relay support for Schiaparelli was now repurposed into acquiring pictures of the impact site. After refining the potential location where Schiaparelli landed, MRO's Context Camera (CTX) was used to look for evidence of the landed parts a day after Schiaparelli's arrival at Mars. Figure 7a shows the Schiaparelli landing site before landing on May 29, 2016 and Figure 7b represents a day after landing. The large black spot in Figure 7b indicates the impact by Schiaparelli, and the white spot its parachute.



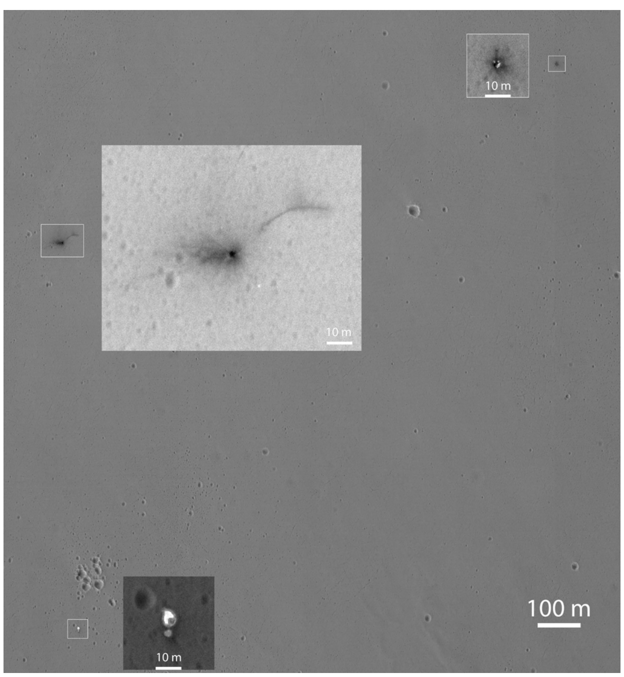
(a) Landing Site on May 29, 2016



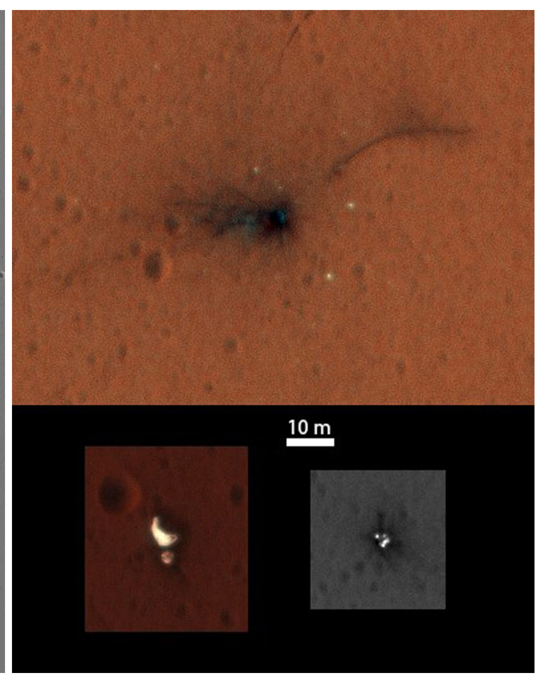
(b) Landing Site on October 20, 2016

Figure 7: Images of the Schiaparelli landing site taken by CTX; before and after landing. Source: NASA/JPL-Caltech.

Based on the information obtained by CTX, the High Resolution Imaging Science Experiment (HiRISE) camera was used to take images that revealed three separate locations showing the lander, the parachute, and the heat shield, as illustrated in Figure 8. The HiRISE image taken on October 25, 2016 during the second planned set of observations (Figure 8a) revealed the lander impact (center left), the front heat shield impact (upper right), and the parachute and rear heat shield (lower left). Finally, the HiRISE picture taken on November 1, 2016 during the third overflight observations period details what is believed to be the main spacecraft's impact location, the lower heat shield, and upper heat shield and parachute (Figure 8b). With this second image, it is noted that wind seems to have moved the parachute, and some of the bright spots around the impact area were confirmed to be from material from Schiaparelli.



(a) Impact Area on October 25, 2016



(b) Impact Area on November 1, 2016

Figure 8: Images of the Schiaparelli impact area taken by HiRISE. Source: NASA/JPL-Caltech.

RETURN TO MRO PRIMARY SCIENCE ORBIT AFTER SCHIAPARELLI SUPPORT

The GTW error was kept within reasonable bounds as the phasing maneuvers OTM-45 and OTM-46 were executed in the pro-velocity direction. These phasing maneuvers moved the GTW error slightly west and outside the mission requirements of ± 40 km for a brief period of time, as can be seen in Figure 4. Meanwhile, the Local Mean Solar Time (LMST) had been on an upward drift towards 3 PM in October 2017 after the execution of an inclination-change maneuver in April 2016 (OTM-44). The plan is to arrest the drift in March 2017 to achieve 2:52 PM LMST at the time of InSight EDL support in November 2018.[8] To avoid interfering with the lunar calibration opportunity for the HiRISE camera on November 20, 2016 and considering the holidays, OTM-47 was scheduled for November 2, 2016 to return to the PSO a month after the Schiaparelli support period. This maneuver was performed in the pro-velocity direction at apoapsis to re-establish the GTW control with a modest ΔV of about 0.2 m/s. OTM-47 performed well within expectations (2.1% overburn).

CONCLUSION

MRO had planned to provide relay support to Schiaparelli for two weeks, of which the first four days were prime. Unfortunately, Schiaparelli did not survive the atmospheric descent and the planned four-day surface mission ended before it could begin. Instead of providing relay support, MRO's CTX and HiRISE cameras made timely observations of the different landed parts of Schiaparelli, including the parachute and heat shield. The images taken by MRO of the impact site were made possible by the accurate phasing that MRO attained. The navigation plan to phase MRO to the prescribed Schiaparelli target location was successfully implemented with the executions of the two pro-velocity maneuvers OTM-45 and OTM-46. Despite a dust storm that materialized in early September 2016 and the execution error in the final phasing maneuver, MRO was only about 10 seconds late from its intended Schiaparelli target position. The predicted phasing offset was well within ESA's phasing requirement of ± 5 minutes and the 3-σ timing uncertainty of 2 minutes following the final phasing maneuver, OTM-46. This phasing accuracy can be better appreciated when compared to the almost 1 minute timing accuracy achieved by MRO to avoid the Comet Siding Spring's incoming particles as it passed by Mars on October 19, 2014.[7] The trajectory file based on the MRO Navigation Team's OD solution on September 26, 2016 was provided to ESA to be transmitted to Schiaparelli while in flight and before separation from TGO. If the Schiaparelli lander had performed nominally, MRO would have risen only 4.02 seconds later than the expected rise time. In summary, the MRO Navigation Team was able to achieve the target parameters well within the phasing requirements.

ACKNOWLEDGMENTS

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APPENDIX A: VERIFICATION OF SCHIAPARELLI OVERFLIGHT GEOMETRY

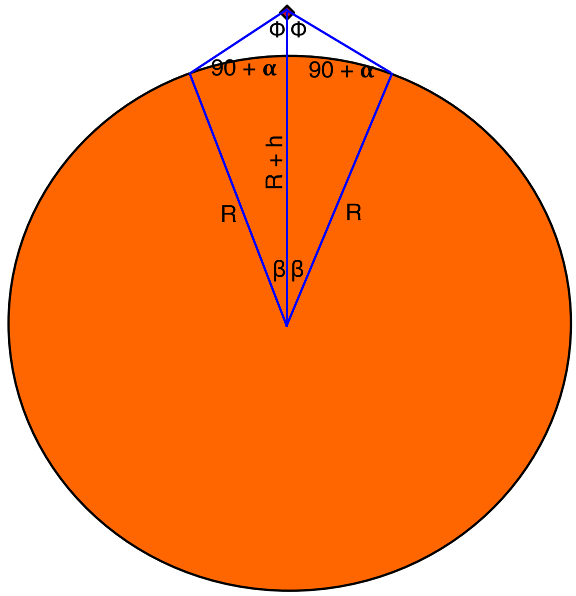

Figure 9: Overflight Visibility Geometry. *Note, Mars equator is in the plane of the paper. Since the MRO orbit is near-polar (92.6°) the orbit is almost perpendicular to plane of the paper.*

Figure 9 shows the overflight geometry when the desired maximum elevation angle (α) is achieved. The time duration for Mars to rotate such that the maximum elevation angle is met can be approximately derived by solving the following equations:

$$\frac{\sin\phi}{R} = \frac{\sin(90^\circ + \alpha)}{R + h} \tag{1}$$

$$\beta + \phi + (90^\circ + \alpha) = 180^\circ \tag{2}$$

where ϕ is the angle measured from the spacecraft location between the Mars center to the point on the Mars surface when the maximum elevation angle is achieved, β is the angle measured from Mars center between the spacecraft location to the point on the Mars surface when the maximum elevation angle is achieved, R is the Mars radius, and h is the spacecraft altitude. Equations 1 and 2 can be solved for ϕ and β by setting α to 30°, R to 3396.2 km, and h to 287.5 km:

$$\phi = \arcsin\left[\frac{R}{R+h}\sin(90^\circ + \alpha)\right] = 52.98^\circ \tag{3}$$

$$\beta = 90^\circ - \phi - \alpha = 7.02^\circ \tag{4}$$

The angle β can then be used to compute the time duration for Mars to rotate when the maximum elevation angle is achieved:

$$\Delta T = \left[\frac{2\beta}{360^\circ}\right] P = 57.7 \text{ min} \tag{5}$$

where P is the Mars rotational period (24.028 hours). Since MRO's period is $\sim$112 minutes, in-plane orbit phasing is limited to within this computed duration, barring an orbit-plane change via a costly out-of-plane maneuver.

APPENDIX B: EDL RELAY TARGET FILES

Coordination between the MRO Navigation Team at JPL and the ESOC Flight Dynamics Team (ESOC-FD) at ESA was established prior to the launch of Schiaparelli and TGO. ESOC-FD provided files which included the EDM overflight target time and corresponding latitude. In return, the MRO Navigation Team supplied the predicted MRO trajectories based on current orbit solutions through the Schiaparelli support period. Table 6 presents the ERTF history, beginning with ERTF-01 which was the basis of Reference 5. ERTF-08 was used for designing OTM-46, the final OSM used to phase to the Schiaparelli overflight target (highlighted in Table 6).

Table 6: ESOC-FD ERTF History for Requested Schiaparelli Overflight Phasing Targets

ERTF	Delivery Date	Days to EDM Target	Target Conditions		Comments
			Epoch (ET)	Latitude (deg)	
01	April 29, 2016	174	20-Oct-2016 17:16:08.182	−2.18	Reference 5
02	May 11, 2016	162	20-Oct-2016 17:18:08.182	−2.16	2 min change in target epoch
03	June 10, 2016	132	20-Oct-2016 17:17:45.182	−2.03	23 sec change in target epoch
04	July 1, 2016	111	20-Oct-2016 17:17:45.789	−2.05	Used for OSM-1 (OTM-45)
05	August 4, 2016	77	20-Oct-2016 17:17:43.789	−2.05	2 sec change in target epoch
06	August 15, 2016	66	” ”	”	ERTFs 06-13 targets same as ERTF-05
07	August 24, 2016	57	” ”	”	
08	September 5, 2016	45	20-Oct-2016 17:17:43.789	−2.05	Used for OSM-2 (OTM-46)
09	September 15, 2016	35	” ”	”	
10	September 26, 2016	24	” ”	”	
11	September 30, 2016	20	” ”	”	
12	October 7, 2016 08	13	” ”	”	
13	October 14, 2016	6	” ”	”	

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