

The Mars Reconnaissance Orbiter Mission: 10 Years of Exploration from Mars Orbit

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Abstract— The Mars Reconnaissance Orbiter (MRO) entered Mars orbit on March 10, 2006. After five months of aerobraking, a series of propulsive maneuvers were used to establish the desired low-altitude science orbit. The spacecraft has been on station in its 255 x 320 km, sun-synchronous (~3 am-pm), primary science orbit since September 2006 performing both scientific and Mars programmatic support functions. This paper will provide a summary of the major achievements of the mission to date and the major flight activities planned for the remainder of its third Extended Mission (EM3). Some of the major flight challenges the flight team has faced are also discussed.

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1. INTRODUCTION

The Mars Reconnaissance Orbiter (MRO) Project is a major element of the Mars Exploration Program (MEP). The spacecraft was launched on August 12, 2005, entered Mars orbit on March 10, 2006, and after 6 months of aerobraking, was established in its low-altitude, solar fixed (~ 3 am-pm) near-circular polar orbit (~255–320 km) [1]. Its one-Mars-year Primary Science Phase (PSP) started in September 2006 with observations characterizing the Mars atmosphere, surface and subsurface. MRO conducted a second Mars year of science observations in an Extended Science Phase (ESP) approved in 2008 by the MEP Senior Review Panel and NASA [2]. As an extended mission, MRO proposes mission extensions as a part of the NASA Senior Review

process. Table 1 summarizes the approved MRO mission extensions through Extended Mission 3 (EM3).

Table 1. MRO Primary Science Phase and Mission Extensions

	Start Date	Completion Date	Objectives/Notes
Primary Science Phase	September 2006	December 2008	MRO Primary Science Mission and Phoenix EDL and surface relay.
Extended Science Phase	January 2009	September 2010	MRO Science Investigations and Phoenix surface relay.
Extended Mission 1	October 2010	September 2012	FY11 thru FY12 – MRO Science Investigations and MER relay and MSL EDL and surface relay
Extended Mission 2	October 2012	September 2014	FY13 thru FY14 – MRO Science Investigations and MSL and MER surface relay.
Extended Mission 3	October 2014	September 2016	FY15 thru FY16 – MRO Science Investigations and MSL and MER surface relay. Arrival and relay support for InSight.
Future Extensions (Requires NASA Approval)	October 2016	TBD	Arrival and relay support for 2016 ExoMars EDM. MRO Science Investigations and Mars Exploration Programmatic Support.

Spacecraft/Payload Description

The MRO spacecraft, shown in Figure 1, is a very capable remote sensing science platform. It carries six science

payloads and a UHF telecommunications radio (Electra) for surface relay. The spacecraft was developed to support atmospheric limb, on planet and regional surface and subsurface survey. A novel capability for Mars is the ability to routinely carry out targeted, high-resolution surface observations. The spacecraft is 3-axis stabilized with large momentum wheels providing stability and control. In order to reduce pointing errors resulting from navigation uncertainties, the orbiter uses an on-board ephemeris driven pointing algorithm that allows for precise surface targeting. To return large volumes of scientific data to Earth, the spacecraft has a powerful telecommunications and command & data handling (C&DH) architecture that communicates on average 16 hours a day with the Deep Space Network (DSN). The science payload for the mission consists of a high-resolution imager (capable of resolving 1-meter-scale objects with 30 cm per pixel from 300km altitude) [HiRISE – High Resolution Imaging Science Experiment], a visible/near infrared imaging spectrometer [CRISM – Compact Reconnaissance Imaging Spectrometer for Mars], an atmospheric sounder [MCS – Mars Climate Sounder], a subsurface radar sounder [SHARAD – Shallow (Subsurface) Radar], a weather camera [MARCI – Mars Color Imager], and a context optical imager [CTX – Context Imager]. In addition to the science payloads, spacecraft radiometric data is used to support gravity science studies. During its aerobraking phase, from April to August 2006, spacecraft accelerometer data were used to characterize the atmosphere above 100 km. A more detailed description of the instruments and investigations can be found in Zurek and Smrekar [3].

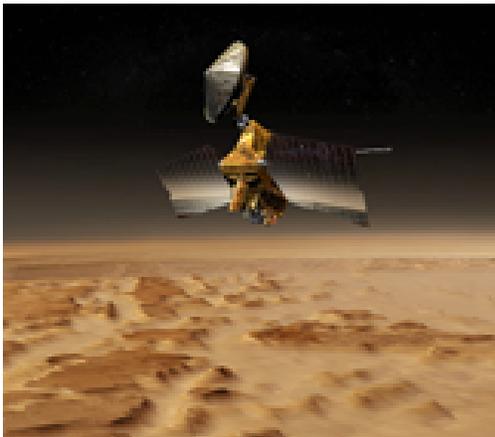


Figure 1. Artist rendering of the MRO Spacecraft

Spacecraft Operability and Target Planning

When not targeting, the MRO spacecraft is normally oriented such that its payload elements remain nadir pointed to Mars. Owing to its gimballed high gain antenna (HGA), the spacecraft can simultaneously acquire science and relay data and return that data to Earth nearly continuously over an orbit (except for periods of Mars occultation or for gaps in DSN coverage). Additionally, the MRO spacecraft can

cross-track roll up to ± 30 deg from nadir to enhance its targeting field-of-view or for higher signal-to-noise radar observations. Gimballed solar arrays allow the spacecraft to maintain power by sun tracking even while rolling. Science surface targets and relay support passes are scheduled and acquired using an on-board flight software targeting module. The targeting module is provided a conflict-free list of observations and relay overflights produced by ground planning software. This list [called the Integrated Target List (ITL)] covers one MRO planning cycle -- two weeks of observations. This ITL contains both rolled (off-nadir, planned for a 2-week period) and nadir (planned weekly) observations. Surface target accuracy is maintained by performing navigation ephemeris updates to the spacecraft twice a week.

The *MRO* orbit and thus ground track walk were chosen so that practically any place on Mars can be seen ≥ 2 times in any 17-day period, using off-nadir rolls. This means that repeat views of the same locale (as needed for stereo or for landing site coverage) can be achieved in a few weeks. Restriction to nadir viewing would increase that time to more than 100 days for low latitude sites (where most candidate landing site ellipses are). With a 112-minute orbit, there are 12-13 orbits each day

2. EXTENDED MISSION 3 OBJECTIVES

Now in its third Extended Mission, MRO is carrying out a remote sensing mission consisting of scientific and programmatic support objectives. The four EM3 science objectives (abbreviated here) are to characterize and better understand:

- Evolution and habitability of early Mars;
- Geologically recent climate variability;
- Modern surface changes; and
- Current atmospheric & polar processes.

The Mars Programmatic objectives for EM3 include:

- Landing site reconnaissance for future missions;
- Support of mission surface operations;
- Critical event telemetry monitoring;
- Surface (UHF telecommunications) relay and asset monitoring; and
- Environmental information for mission design and surface operations.

The overall mission timeline for EM3 is shown in Figure 2. It includes Mars seasons, global dust storm seasons, the solar conjunction command moratorium time period, spacecraft roll limits, local mean solar time (LMST) drift and associated local true solar time (LTST). Predicted daily data volume estimates are also shown. During EM3, *MRO* will be maintained in its nominal low altitude science orbit

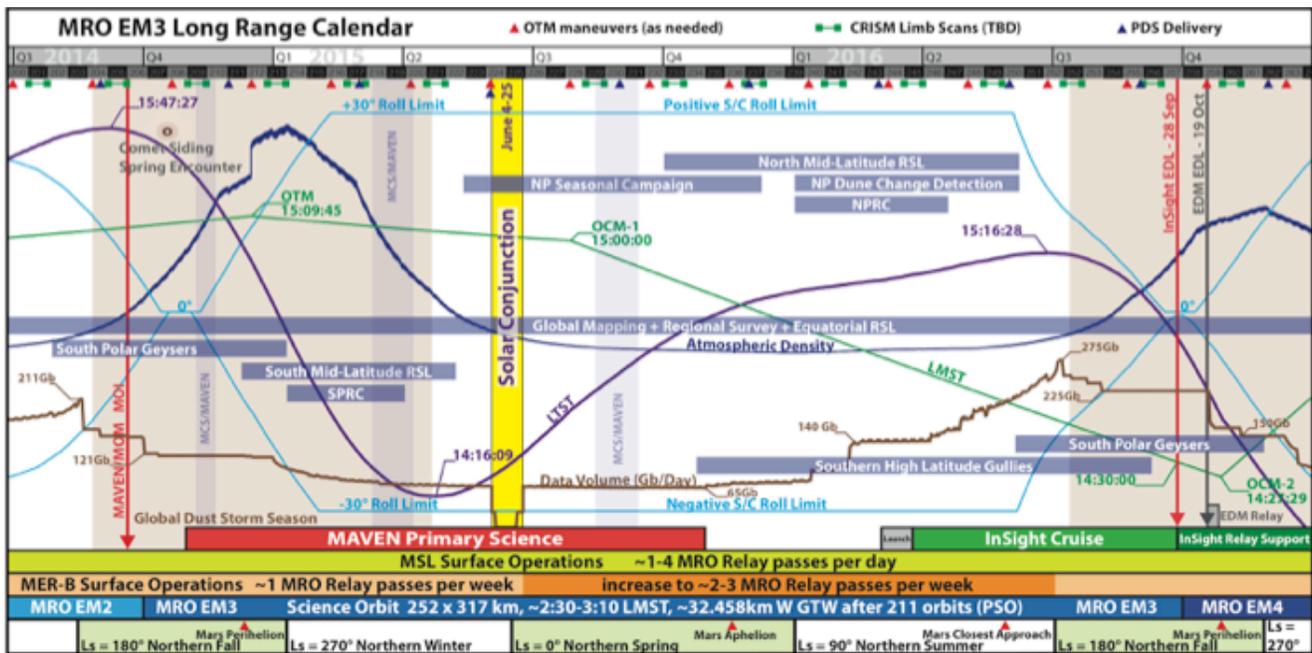


Figure 2. *MRO* Extended Mission 3 Timeline (July 2014–December 2016)

with an orbit of 255×320 km and 93° inclination. Owing to programmatic support agreements, *MRO* will initiate a slow drift and change its orbit ascending node to 2:30 pm LMST to coincide with InSight arrival and its EDL event.

Special science investigation focus times are shown in Figure 2 as blue horizontal bars (e.g., north polar residual cap (NPRC), north polar dune change detection, etc.). Additionally, special science observing campaigns of opportunity are shown as shaded bars: This includes the special Comet Siding Spring encounter campaign and the *MRO-MAVEN* science synergy campaigns, planned when *MRO* and *MAVEN*-periapsis have similar local times.

For most of EM3, *MRO* is not restricted within its allowable spacecraft roll range. However, when the Earth beta angle exceeds 55° , the range of roll limits during downlink is restricted (shown as a cyan line), due to limits on the High-Gain-Antenna (HGA) gimbal. This restricts the ability to target during those planning cycles and maintain communications with the DSN. However, non-contact telecom windows can be defined to accommodate high priority targets, essentially trading downlink data volume for timely view opportunities.

3. SELECTED EXTENDED MISSION SCIENCE RESULTS

The *MRO* mission was developed under the “Follow the Water” theme of the Mars Exploration Program (MEP). Water was—and remains—the common thread uniting the major objectives of the program:

- **Life:** Water is essential to life as we know it. Did it get a start on Mars, and is there evidence of its origin and evolution at/near the surface today? *MRO* has made major contributions to this by detecting minerals that characterize the temperature and acidity of ancient water environments.
- **Climate:** Mars once had great volumes of liquid water flowing across its surface and altering the minerals in its crust. What caused the radical change to a more arid climate today? Have there been episodic water releases in more recent geologic times? *MRO* investigates the processes of climate change by characterizing weather and climate processes on Mars today. It also has characterized volatile reservoirs (ice cap layering and subsurface, non-polar ice deposits) that may have been active on obliquity/eccentricity time scales of 100 Kyr to 1 Myr.
- **Geology & Geophysics:** Parts of the ancient Mars surface survive today and may hold clues to geochemical and possible biological activity on early Mars. The patterns of desiccated ground and impact exposed bedrock provide further clues to the geologic evolution of the planet’s crust. The Martian surface continues to change today, with over 400 new impact craters identified in its 9 years of observation. *MRO* has captured these and other changes thanks to its unprecedented (from orbit) spatial resolution and mission longevity.
- **Preparation for Humans:** Observations by *MRO* instruments are critical to the early identification and characterization of potential landing sites for future robotic and human missions. For human missions, water—whether in the form of ground ice, vapor, hydrated minerals, or briny water—is a highly valued resource. Thus, observations of

water in all of its forms, directly or indirectly, by MRO are crucial for both science and resource prospecting for future missions.

MRO Science Highlights

The Martian atmosphere and crust contain clues as to their evolution throughout the history of the planet. That history is frequently divided into three ages; MRO has made major contributions to understanding all 3 of those periods.

Ancient Mars (the first several billion years)

- Morphologic and mineralogical evidence (phyllosilicates, opaline silica, carbonates, sulfates) of episodic alteration by water of surface materials early in Mars history buried later by unaltered materials (Figure 3).
- Sedimentary rocks covering many regions of Mars showing indurated fractures that imply groundwater movement, cementation and alteration.

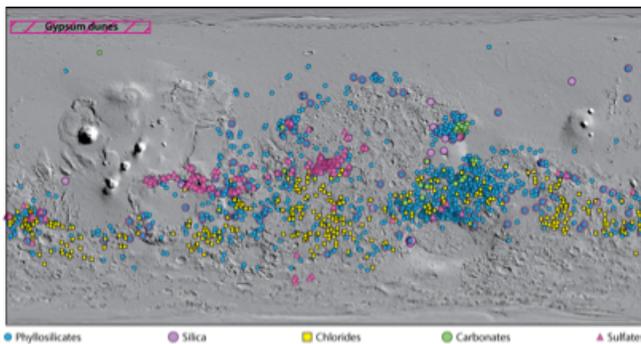


Figure 3. MRO has mapped many thousands of outcrops of minerals that must have formed in liquid water. The variety of minerals provides clues to the alkalinity and temperature of the water environment in which alteration occurred. (Ehlmann and Edwards [4]; CRISM / JHUAPL / JPL / NASA)

- Evidence that the Tharsis plateau is underlain by a large elliptical basin suggests an impact origin of the hemispheric dichotomy
- Inverted stream-beds suggest wetter conditions with extended (perhaps impact rainfall driven) run-off
- Analysis of *MRO* and *Mars Odyssey* compositional data yields an estimate of the amount of carbonate exposed at the surface that is only a few times the present atmospheric mass; this indicates that, if there was a massive atmosphere on an early, wet Mars, it was not lost by carbonate formation, suggesting that loss to space was the primary mechanism drawing down the atmosphere [5].

Geologically Recent Mars (last billion years)

- Indications of geologically young gullies shaped by water (possibly occurring even today)
- North polar layered terrains may be as young as ~10 Myr in age; those in the south are much older (~100 Myr or more)
- Ice cap base flatness of north polar cap implies chondritic internal heat production & a cooler, more rigid crust than previously expected
- Internal layering in the northern ice cap and exposed layering elsewhere suggest two dominant time scales in their formation, probably driven by obliquity and orbital cycles [6]
- Thick (> 100 m) remnant ice deposits in mid-latitudes preserved beneath debris blankets; these may be the physical remnants of the last “ice age” cycle (discussed above) [7]
- A combination of morphologic and radar data indicate the presence in Acidalia (northern mid-latitudes) of a subsurface ice layer ~40 m thick over an area as big as Texas and California combined [8]

- Internal tracing of the chasma of the north polar cap, showing their presence and progression with depth; westward migration of the chasma is consistent with theory of formation by sublimation on western slopes and deposition on eastern by katabatic winds [9]

- Enough CO₂ ice buried in the south polar cap that, if exposed and sublimed into the atmosphere, would double the present atmospheric mass [10]

Present Mars (last few hundred years and ongoing)

- Ongoing change: Impacts, surface avalanches, seasonal & interannual processes (Figure 4).
 - Over 400 new impact craters identified; this enables assessment of modern cratering rate, which is roughly consistent with extrapolations of the rate curves for larger impacts
 - Many sand dunes are observed to move, dispelling the notion that they are all relics of an earlier climate [11]
 - Observations of the seasonal CO₂ cap retreat indicate that “jetting” of the CO₂ as it sublimates beneath semi-transparent ice produces a wide range of morphologic patterns (e.g., “spider-like”); this also triggers numerous small landslides (“fans”) and small gully formation on the dunes at high latitudes (Figure 5)

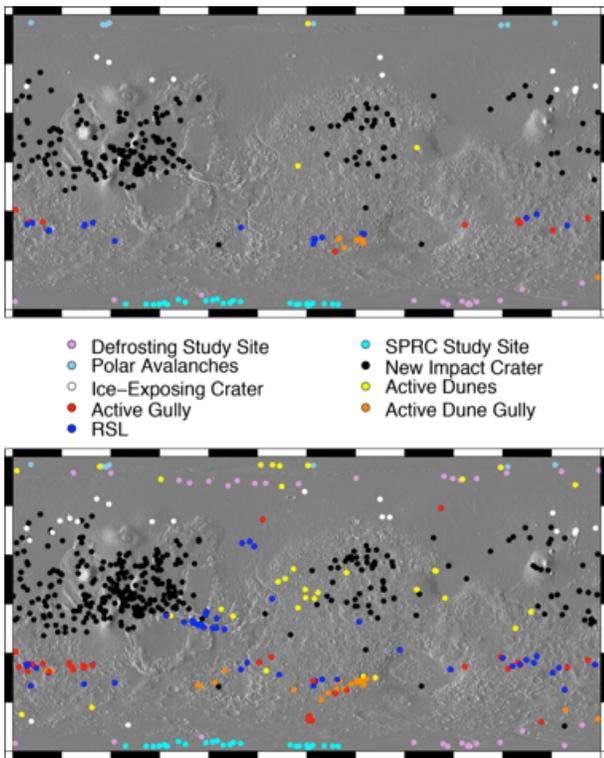


Figure 4. Progress in discovering, characterizing, and understanding active surface phenomena is accelerating as more repeat coverage and a longer temporal baseline are realized by *MRO*'s continued observations. Figure shows locations for 9 categories of active surface processes in early 2012 (top) and 2 years later.

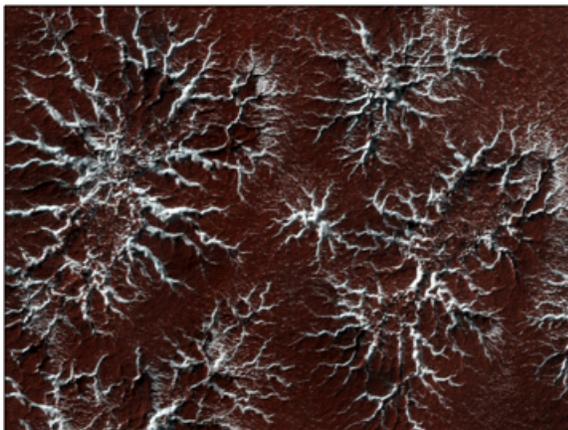


Figure 5. Sublimating CO₂ ice carves spider-like patterns in the Mars surface each spring (HiRISE / U. Arizona / JPL / NASA).

- Ongoing extension by *MRO* of the climatological records of temperature, dust & water vapor started by *MGS* are revealing new patterns of distribution with implications for transport

- Dust is definitely not uniformly mixed with altitude—the origins of a mid-atmosphere maximum in dust mixing ratio is challenging atmospheric models (Figure 6).

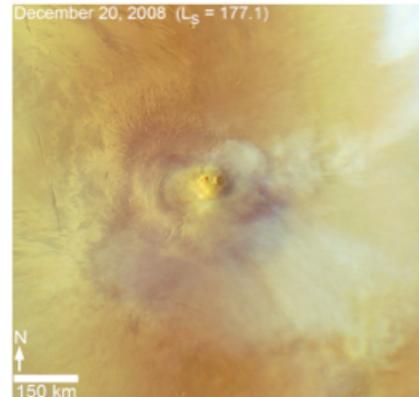


Figure 6: This dramatic image of a large spiral dust cloud over the summit of the Arsia Mons volcano suggests one way that dust might be injected into the mid-atmosphere. (MARCI / MSSS / JPL / NASA)

- A “leaky” atmospheric trap for water vapor as the diurnally varying temperature wave (a “thermal tide”) sweeps around the planet with the cold phase freezing water vapor and limiting its vertical transport [12]
- A significant fraction (~20%) of CO₂ frost accumulation occurs as atmospheric snow, augmenting frost formation at the surface [13]
- Regional dust storms occurring during the large dust storm “season” (southern spring and summer) tend to group in 3 distinct periods from mid-southern-spring into the last third of southern summer (Figure 7).

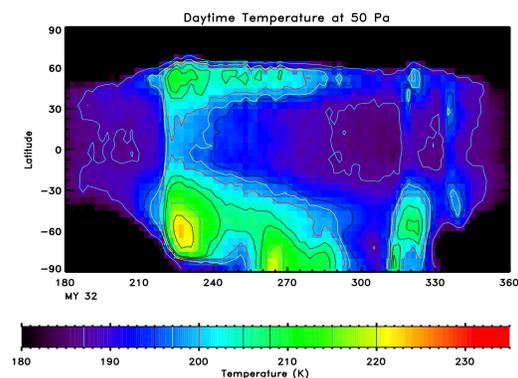


Figure 7. Regional dust storms produce warm mid-atmosphere temperatures during the last planet-encircling dust event season. The pattern of 3 events tends to repeat to some degree in each Mars year (D. Kass, in preparation, MCS / JPL-Caltech / NASA).

- Recurring Slope Lineae (RSL): These are linear streaks on steep walls of craters or canyons that darken during the warmest part of the year, extend downslope, and then fade when cooler temperatures return (Figure 8). The best hypothesis is that these are due to water seeping down the slopes, darkening the material at the surface

- Originally found in the mid-southern latitudes where ground temperatures are warmest during southern spring and summer when Mars is close to the perihelion of its significantly elliptical orbit [14]
- Now also detected in equatorial latitudes on sun-facing slopes and a few in the northern hemisphere where maximum temperatures are cooler in the aphelic spring/summer season [15]
- Hydrated perchlorate salts were detected by MRO in associated with RSL features; such salts can depress the freezing point of a brine such that the brine stays unfrozen for a much larger part of the day and on more days in the warm seasons [16].

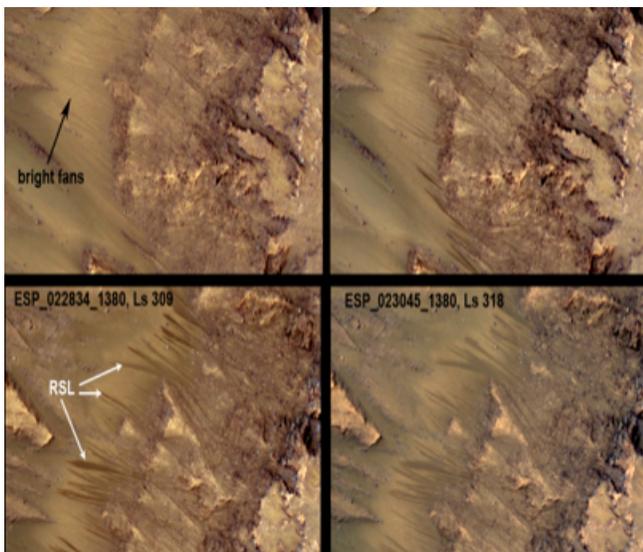


Figure 8. Recurring Slope Lineae (RSL) are linear areas that darken during warm seasons (upper right), extend down slope (lower left) and then fade in cooler seasons (lower right). These are in Palikir Crater in the Newton basin. (HiRISE / U. Arizona / JPL / NASA; McEwen et al. [14])

Special Observations: Comet /2013 A1 Siding Spring

In January 2014, a first-time Oort Cloud comet was detected on a possible collision course with Mars. In the end, Comet Siding Spring (CSS) had a close approach with Mars at a range of 140,000 km (one-third of the Earth-Moon distance) in October 2014. This rare astronomical event presented a unique opportunity to make a series of special scientific

observations utilizing the capabilities of the Mars Reconnaissance Orbiter (MRO) spacecraft and its science instruments. The comet's close approach motivated two activities: (a) the development of an off-planet instrument observing campaign during the close encounter and (b) the development of special spacecraft protection measures owing to the particle threat from the comet's debris field. The latter measures consisted primarily of a two-burn navigation strategy that successfully positioned the spacecraft behind Mars at the time of the arrival of the peak flux from the comet debris field, which was moving at ~55 m/s relative to Mars. This positioning was achieved within one minute of the desired offset time, despite the atmospheric drag forces that MRO experiences due to its low altitude. A more detailed description of the CSS navigation strategy can be found in Menon, et. al. [17]

Although designed to observe the Martian surface and atmosphere, MRO scientists and spacecraft engineers developed a major off-planet observing campaign utilizing the full science suite of MRO instruments: HiRISE, CRISM and CTX performed targeted comet imaging observing the nucleus and coma. MCS, MARCI and SHARAD made Mars atmospheric measurements before and after encounter searching for change due to atmospheric heating by the high-speed cometary particles. All told, MRO performed more than 60 special off-planet slews to allow its targeting instruments to observe the comet over a three day time period around closest approach. HiRISE successfully imaged CSS ~12 days prior to closest approach enabling a late ephemeris update that ensured the comet would be—and it was—in the imager fields-of-view at closest approach. All data taken were successfully returned to the ground and distributed to the science teams for analysis.

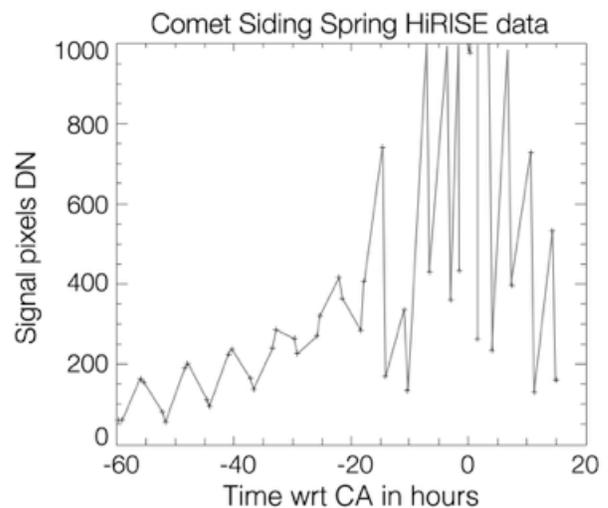


Figure 9. The early variations of observed reflectance suggest an ~8 hour rotation period for the nucleus. The greater variability observed near closest approach (CA) is due to non-uniform properties of the comet nucleus. (HiRISE / U. Arizona / JPL / NASA)

The MRO observations revealed several key features of this relatively unknown Oort Cloud comet. In particular, MRO found higher-than-expected non-gravitational forces (comet jet activity necessitating the ephemeris update) and an apparent rotation period for the nucleus of ~8 hours (Figure 9); it also provided the only images in which the nucleus is resolved placing constraints on its size. MRO also detected an increased ionospheric signature on the night side, produced by the incoming particles.

From an engineering perspective, this activity was well beyond the normal scope of activities for the MRO mission. Overall, the comet campaign showed the ingenuity of the scientists and engineers in developing the necessary instrument parameter sets, spacecraft sequences, and special protection measures that worked flawlessly together to keep the orbiter safe while taking full advantage of this unique comet encounter.

4. EXTENDED MISSION 3 PROGRAMMATIC SUPPORT FUNCTIONS

NASA has tasked the Mars Reconnaissance Orbiter Project to provide essential mission support to designated ongoing and future missions, including international missions. These tasks, in which some of the resources of one mission in the Mars Exploration Program are utilized to support other Mars missions (including the Discovery Program *InSight* mission), have two principal goals:

- To lower the risk of losing highly valuable spacecraft assets (such as happened with Mars Polar Lander) by providing critical event coverage for post-flight analysis; and
- To substantially enhance the scientific return from surface missions, principally by providing a lower power (for the landers and rovers) relay path to return surface mission data.

Programmatic Support Functions

MRO's Programmatic support functions can be divided into five categories of support, four of which require some use of science instruments:

1. Landing site reconnaissance for future missions includes:
 - Identification of specific sites with geologic units at which compelling in situ measurements needed to achieve the landed mission's goals can be made;
 - Characterization of these same sites to determine the distribution of key materials, their stratigraphic relationships, and those exposures of the surface (i.e.,

those free enough of dust, dunes, or talus) that could provide access at spatial scales not resolvable from orbit;

– Certification of the site to be acceptably free of hazards. This entails:

- High-resolution imaging to determine local slopes;
- Very high-resolution imaging to detect surface hazards (rocks, pits, etc.);
- Acquisition of atmospheric data at the appropriate seasons to develop environmental models and the associated temporal variability to design and simulate flight performance of the landing vehicle.

2. Support of mission surface operations, which includes:

– Atmospheric dust monitoring for solar powered landed craft (e.g., Opportunity);

– Observation of the surface before and after landing to support traverse planning for efficient and scientifically productive roving (e.g., Curiosity).

3. Monitoring of critical phases permits assessment of performance and margins to aid future entry, descent, and landing (EDL) design or determination of contributing factors in the event of a failure. This may include:

– Capture and return of EDL data (e.g., telemetry and tones).

– When aerobraking, monitoring of lower atmospheric dust events that can raise densities at aerobraking altitudes.

– Near-real time observations of the atmospheric state leading up to EDL, which may permit in-flight updates of spacecraft parameters and reconstruction of the atmospheric state during entry.

– Though not officially required, this has also included imaging during descent (e.g., HiRISE images of Phoenix and MSL on their parachutes during descent) and images of the lander/rover and associated hardware (parachute, backshell, heat shield, sky crane, etc.) on the surface post-landing (Figure 10).

4. Surface relay, which includes forwarding commands to, and returning data from, landed spacecraft assets.

5. Environmental information for mission design includes:

– General characterization of the atmospheric state (temperature, pressure, density, winds, dust opacity) as a

function of time-of-day and season, together with their interannual variability using observations and atmospheric models constrained by observations;

- General characterization of the surface environment (albedo, trafficability).



Figure 10. MRO HiRISE captures MSL during descent on its parachute (left). The backshell with parachute attached is shown on the surface several sols after MSL landed.

Specific mission support tasks in EM3 include:

- MSL *Curiosity* [MEP]: Relay (twice a day, averaging ~450 Mb/sol; 75% of the MSL science data have been relayed through MRO and two major rover software uploads have been forwarded to the rover). Orbital observations guide MSL to wheel-friendly paths and to targeted clay and sulfate deposits.
- MER-B *Opportunity* [MEP]: Relay (once per week, with more passes added during winter to offset MER-B power limitations in using *Mars Odyssey* as a relay). Orbital observations to guide MER to the most promising aqueous mineral deposits on the Endeavour crater rim and atmospheric monitoring to avoid power shortages during dust storms.
- *InSight* [Discovery Program]: Post-solar-conjunction in EM3, *MRO* will maneuver to change its LMST so that it can view and record EDL, as well as monitor the atmosphere prior and immediately after EDL. Landing site observations have been mostly completed, but it is anticipated that there will be some follow-up requests. MRO Electra will then provide contingency relay support for the *InSight* CE-505 radio, while remaining prime for the MSL Electra Lite radio. As *InSight* is solar-powered, MRO will watch for

dust and other weather events, particularly during their key deployment activities in the first 60 sols.

- ExoMars EDL Demonstration Module (EDM) [ESA]: Arrives ~3 weeks after *InSight*. At the current time, the commitment to the battery-powered EDM is for relay and post-landed imaging. To provide the best possible relay performance in support of the EDM during its short (4–10 Sol) mission, MRO will turn all instruments (except HiRISE) off for the first 4 sols and then use its relay quiet mode for subsequent relay passes until end of the EDM mission. During EM3 HiRISE is acquiring high-resolution data for the EDM landing site while MCS and MARCI monitor atmospheric state leading up to EDL.
- 2020 Mars Rover [MEP]: Characterization and certification of landing sites for this mission is well underway, with continuing observations of the ~10 sites that emerged from the August 2015 Second 2020 Mars Landing Site Workshop. Atmospheric observations in the season of landing will be acquired to aid design of EDL.

- 2018 ExoMars Rover [ESA]: Although still in discussion, the MRO Project is expecting NASA to direct it to provide characterization and certification for the landing sites for this mission starting in EM3.

Transition to Earlier LMST for InSight EDL

The maneuver plan to change the *MRO* orbit node is shown in Figure 11. It consists of three major orbit correction maneuvers (OCM): OCM-1, OCM-2, and OCM-3 and will require 40.6 m/s (22 kg of propellant). The OCMs are small inclination change maneuvers and are used to initiate and control the nodal drift in local mean solar time. Key in the support plan is for *MRO* to be at 2:30 pm LMST when *InSight* arrives for its EDL event. Additionally, because of spacecraft design considerations *MRO* will be kept within its validated local true solar time range: 2:00 pm LTST < 4:00 pm LTST. This means that OCM-2 is a near-critical maneuver in that it will stop the LMST drift and put the spacecraft back on a course to later LMSTs.

On July 29, 2015, *MRO* executed OCM-1 and initiated its drift to 2:30 pm LMST. The maneuver magnitude was 5.4 m/s (2.0 kg propellant). This was the largest maneuver the spacecraft has performed since establishing itself in its primary science orbit in 2006. The attitude control and propulsion subsystems performed perfectly and navigation predicts that *MRO* will arrive at an LMST of 2:29:40 pm at the time of *InSight* EDL, well within acceptable LMST tolerances. Orbit synchronization for the time of *InSight* EDL will start with orbit synchronization maneuvers (OSM) in May 2016. A detailed description of the navigation transition strategy to earlier LMST can be found in Wagner, et. al. [18]

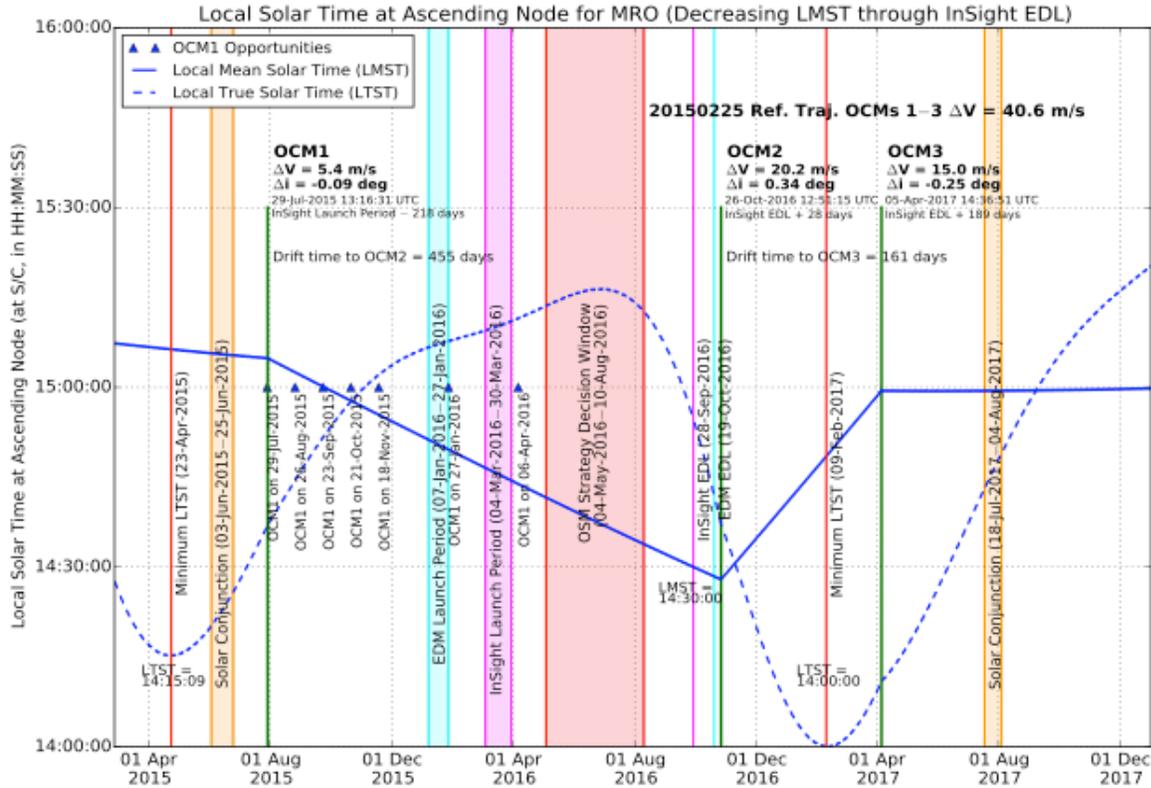


Figure 11. Transition to Earlier Local Mean Solar Time for InSight EDL Support

2016 InSight Launch Suspension

On December 22, 2015, NASA announced the suspension of the March 2016 InSight launch. This decision eliminates the need for any *MRO* flight support (EDL or surface operations) for InSight in 2016. Decisions on arresting or altering the drift in the *MRO* LMST will be made in early 2016.

5. FLIGHT AND MISSION OPERATIONS CHALLENGES

Now entering its 10th year of flight, the *MRO* vehicle remains fully capable of carrying out an ambitious science observing plan and the programmatic tasks assigned to it. The orbiter (i.e., the spacecraft and payload) is fully operational within all required performance regimes. Known risks and previous in-flight anomalies [19,20] do not immediately threaten operation of the orbiter for further science observations or for support of current and future landed missions. Robust margins have enabled mitigation of the normal aging effects on both spacecraft and payload. Spacecraft systems continue to operate reliably, and all

engineering subsystems except telecommunications have full redundant capability; only Inertial Measurement Unit 1 (IMU-1) has started to show end of life conditions. The spacecraft has exhibited some unexpected C&DH behaviors at times, but the flight team has been able to quickly recover the spacecraft and restore normal operations. Instrument produced EMI has created challenges for the performance of the surface relay link but procedures have been developed to mitigate that effect. To support an evolving Mars Exploration Program, relay capability has been expanded several times over the pre-launch architecture.

Telecommunications

The Ka-band exciter in the Small Deep Space Transponder Unit 1 (SDST-1) has failed and the RF #1 waveguide transfer switch is stuck in an intermediate (nearly closed) position. These failures occurred in 2006 during aerobraking, after which *MRO* has only used its X band system. No further use of the Ka-band system (a technology demonstration experiment) or attempts at moving the RF switch are proposed, except as a final recourse in case of failure in the remaining X-band high-rate path. Telecom performance in its current hardware configuration meets all of the needs of the mission.

Inertial Measurement Units

In 2013, the Laser Intensity Monitor (LIM) current for the Y-axis of the IMU-1 began to decline in a manner consistent with ~4–5 months of use remaining before reaching an end-of-life condition. In order to maintain IMU redundancy for safe mode operations, a swap to IMU-2 was commanded in August 2013. IMU-2 has been performing nominally, with a LIM profile consistent with beginning-of-life conditions.

It is expected that IMU-2 will continue to be operational for its 10-year design lifetime, and *MRO* will be able to support the prime mission of the Mars 2020 rover. However, loss of both IMUs would result in the end of mission as an IMU is necessary for safe mode operation. As a contingency measure, the project is developing an All-Stellar (AS) attitude determination mode that uses the orbiter's star trackers, allowing spacecraft operations to continue without the IMUs powered. Development and implementation of AS will take up to two years. Given the short lifetime of IMU-1, an unexpected catastrophic failure of IMU-2 might not leave enough time for the AS mode to be in place, so the *MRO* Project started the development of this capability in FY14. This protects future science and programmatic activities, with the caveat that the ability to acquire unsmearred very-high-resolution HiRISE images is yet to be demonstrated.

Command & Data Handling Resets and Side-Swaps

In the 9.5 years since launch, the spacecraft has experienced 6 resets of the C&DH unit, and 5 unrequested side swaps to the redundant C&DH side. The root cause of these incidents has not yet been determined, and it is expected that these events will continue to occur at roughly the same frequency. Experience indicates that similar events in the future will cause a brief disruption in nominal operations, so they are not seen as a risk to normal flight activities. All safing incidents have been properly handled by on-board fault protection and both sides of the spacecraft avionics have demonstrated full functionality. Figure 12 shows *MRO*'s side-swap and reset history and summarizes all *MRO* safing events. Since the frequency of these events occur approximately every nine to fourteen months, the flight team has developed special methods to restore the spacecraft to nominal operations in ~4 days. For known safe mode entry events, it takes about 48 hours to recover the spacecraft to relay operations and 96 hours to restore full science observational capabilities.

Performance Impact of Instrument Produced EMI on the Electra UHF link

Several *MRO* science instruments did not meet radiated emission requirements in the UHF band in which Electra operates. The resulting electromagnetic interference (EMI) from those instruments significantly degrade Electra's UHF receiver performance or even lead to lock onto spurious signals rather than the intended radio signal. Power-off of the instruments during relay poses a risk to the instruments

and would significantly impact *MRO* science operations. To reduce these impacts, Electra's software was reconfigured after launch to modify the transceiver's signal processing algorithms, implementing a digital filter that attenuated CRISM EMI to an acceptable level. In addition to the digital filter, MCS is put into a standby mode that minimizes interference. This payload configuration for UHF relay has come to be called "relay quiet mode" and is implemented for all relay passes. In relay quiet mode (RQM), CRISM is not observing, SHARAD is not transmitting, and MCS is paused at a particular attitude of its viewing apertures. HiRISE has no detectable EMI, while MARCI and CTX have minor levels, so those instruments are permitted to operate normally during relay passes.

The implementation of RQM (used first for the Phoenix mission) via ground scheduling software, spacecraft constraint checking tools, and relay block design has worked well to protect the relay link from the undesirable effects of EMI. However, RQM has introduced a measure of complexity into *MRO*'s integrated relay and science planning process, and the use of RQM has paradoxically prevented *MRO* from routinely observing sites where it supports daily relay, such as Gale Crater—a site chosen largely on the basis of *MRO* data! In an attempt to help remedy some of this, the project is evaluating an option that would allow CRISM to observe on the UHF frequency used for the Curiosity rover where the CRISM EMI effects are less detrimental to the relay link.

Expanding Electra Relay Capability

As noted, the Electra UHF radio is a software programmable radio with the ability to operate at different UHF frequencies. There were few system-level requirements levied on *MRO* relay capability pre-launch. As such, the original capability was designed assuming nadir overflights and relay communications with a single lander at a fixed data rate. Based on predicted link performance, the fixed data rate could be changed on a pass-by-pass basis. This capability was sufficient to support relay for the 2007 *Phoenix* lander which used a CE-505 radio at fixed data rates.

With the arrival of the *Curiosity* rover in August 2012 and its use of an Electra-Lite radio, *MRO* relay capability was expanded. The first major update was to use the spacecraft crosstrack roll capability to point at the surface asset during relay. While this was done to improve UHF link performance, it was further modified to allow HiRISE to target off-nadir (within certain roll ranges) during relay passes. The second major update was to the Electra flight software to include adaptive data rates (ADR). The ADR capability permits the data rates used for the UHF return link to be autonomously increased during a relay pass when operating with a cooperative radio (i.e. Electra-lite) on the surface. This has been a tremendous boost to UHF data return. Rather than being limited to a single return rate of 128 kbps (like Phoenix) during a pass, the current link can

start at a low data rate and step up its data return rates to 2048 kbps.

For the upcoming *InSight* mission, relay capability will be expanded again. The proximity of *InSight*'s Elysium Planitia landing site and *Curiosity*'s Gale Crater location creates a contention for relay services that impact both missions. With a separation distance of only 500 km, MRO will overfly both of these missions in a matter of minutes, necessitating MRO to support relay with *InSight* and *Curiosity* on the same overflight. As a result the MRO relay architecture will be updated to support a new capability termed "split-pass relay." It is a major update to the MRO relay system and impacts many different project elements: mission planning, science planning, spacecraft constraint checking as well the development of a new series of spacecraft blocks to implement the capability onboard. In addition to the MRO impacts, MaROS the Mars relay

ground planning interface will have to go through a major update to support this new capability.

MRO relay capability has been expanded without changing the existing spacecraft (bus) flight software. New capabilities are implemented by changes to the spacecraft relay block design, ground planning scheduling/constraint software, relay operational procedures, and in the case of ADR, a new Electra flight software load. Such changes are not trivial and require design and development cycles. Rigorous functional and regression testing of the new capabilities are also required prior to implementation. Without additional resources, such expansions of capability require a reprioritization of ongoing activities.

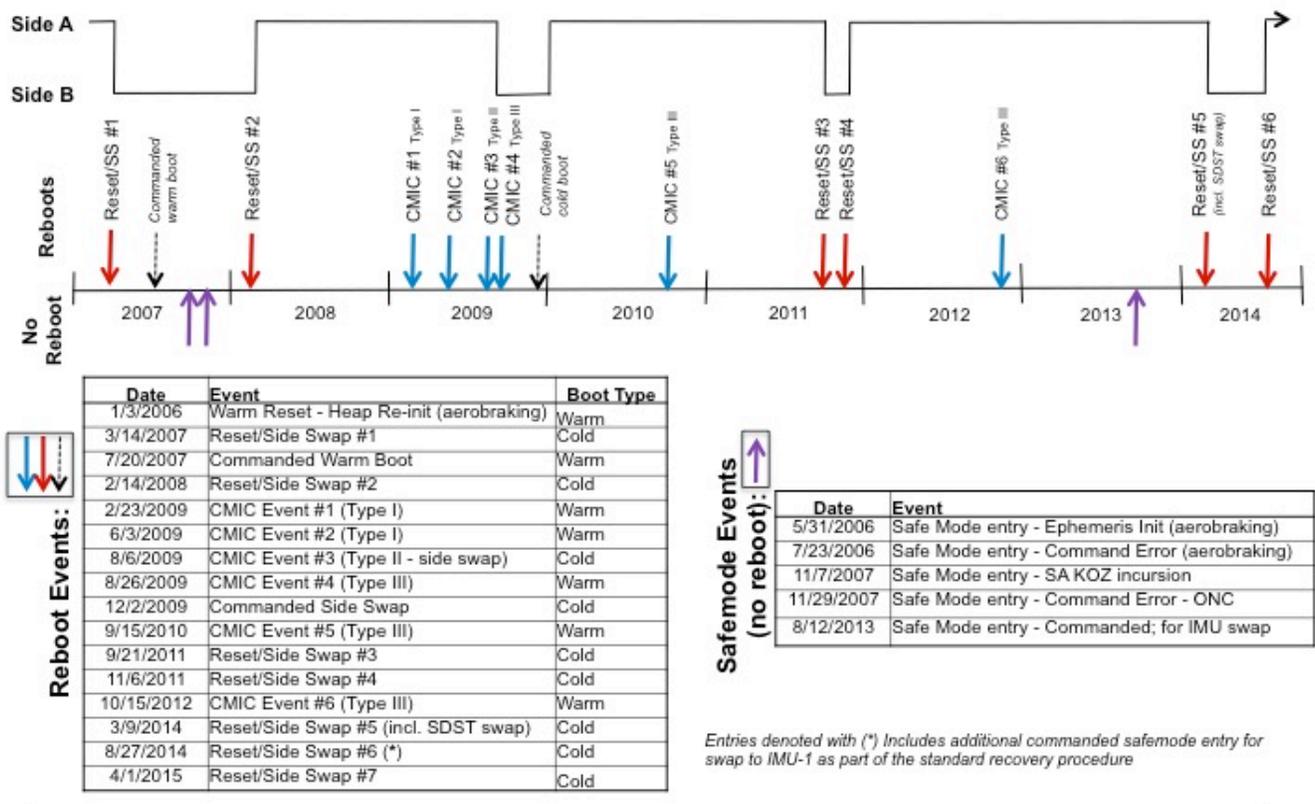


Figure 12. MRO Safe Mode and Side-Swap History

6. SUMMARY

The *Mars Reconnaissance Orbiter* has entered its 10th year of flight. Overall, the spacecraft has performed superbly since it has been on station in its primary science orbit. Due to its dual-mode mission capabilities, the MRO spacecraft has become the workhorse of the Mars Exploration Program supporting both science for a variety of disciplines and programmatic objectives for many missions.

MRO's powerful suite of science instruments continues to unveil Mars in unprecedented detail. The MRO science investigations show that Mars is a diverse planet with a complex geologic history. In particular, the diversity of early water-rich environments shows preservation potential for signatures of ancient life, if it ever developed. Furthermore, the longevity of the mission and the higher spatial resolutions of its instruments, whether viewing the surface, atmosphere or subsurface have revealed a planet where the processes of change are still at work. This is the new Mars: a dynamic, diverse planet throughout its history, including today.

There is more to be learned. Remarkably, the MRO instruments retain their essential capabilities, even as they are now in their 10th year of operation in Mars orbit. Notable metrics include:

- Over 250 Terabits of Science Data returned
- Acquisition of over 150,000 targeted images, and image equivalents:
 - 95% of the planet imaged at 6 m/pixel (CTX)
 - 2.4% imaged at 30 cm/pixel (HiRISE)
 - 83% of planet covered in 72 spectral channels at low opacity (CRISM)
 - Daily Global Maps (MARCI) for ~ 5 Mars years (40,000 images)
 - Atmospheric Profiling (MCS) on 13 orbits per day for ~ 5 Mars years (127 million soundings)
 - Shallow, Subsurface Soundings (SHARAD) covering nearly half the planet (~18,000 observing strips)

In addition to its science achievements, MRO has significantly enhanced the safety of the landing phases of both the Phoenix and MSL missions by identifying safe landing zones and returning critical event (EDL) telemetry for post-flight analysis.

As MRO moves into the future, spacecraft capabilities and operations processes continue to be refined for its dual mode mission of science platform and relay satellite. Preparations are well underway for the anticipated new demands that the *InSight* Lander and the ExoMARS EDL Demonstration Module (EDM) will place on *MRO* capabilities. With large fuel reserves (225 kg) and significant subsystem life and redundancy remaining, the MRO spacecraft is expected to

stay on-orbit as a flagship of the Mars Exploration Program for many years to come.

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BIOGRAPHY



Dan Johnston received a B.S. in Aerospace Engineering from the University of Texas in 1984 and an MSE from the University of Texas in 1989. Since joining JPL in 1989, he has participated in the development and flight operations phases of the Mars Observer and Mars Global Surveyor missions. Prior to joining JPL, he was employed with McDonnell Douglas Astronautics in Houston, TX, in support of STS (Shuttle) rendezvous flight planning. Currently, Mr. Johnston is the Project Manager of the Mars Reconnaissance Orbiter Project.



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