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The Mars Reconnaissance Orbiter Mission: Continuing a Record of Exploration from Mars Orbit

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Abstract

The Mars Reconnaissance Orbiter (MRO) has been on station in its low altitude, sun-synchronous, primary science orbit since September 2006 performing both scientific and Mars programmatic support functions. The spacecraft is a very capable remote sensing science platform carrying six science payloads supporting seven investigations and a UHF telecommunications radio (Electra) for surface relay. Developed to support a mix of nadir mapping and targeted, high-resolution surface observations, the spacecraft's powerful telecommunications and command & data handling (C&DH) subsystems communicate an average of 16 hours a day with the Deep Space Network (DSN). To date, more than 300 TB of scientific data has been returned to Earth. All of the original science payloads are active with standard and new observing modes contributing to the advancement of Mars science through peer-reviewed paper publications and the timely dissemination of their data to the science community as a whole. Results from the science teams have revealed an amazing diversity of ancient aqueous environments and ongoing surface change is evident through gully formation, avalanches, and cratering. Extending the MRO-MGS climate record to a decade of Mars years is contributing to a better understanding of current atmospheric and polar processes. In addition to its fundamental scientific objectives, MRO is a critical element of NASA's Mars Exploration Program (MEP) providing needed infrastructure support for landed and future missions. Using its Electra telecommunications payload, MRO provides landers and rovers critical event coverage during their entry, descent, and landing (EDL) phases and UHF relay support once they are on the Martian surface. MRO's high-resolution imagers are used to scout potential landing sites and certify safe zones for landing. As MRO begins its Fourth Extended Mission, the spacecraft remains fully capable of carrying out an ambitious science observing plan and the programmatic tasks assigned to it. In addition to highlighting recent discoveries of the mission, this paper describes recent challenges the spacecraft engineers have faced in flight and the plans for extending spacecraft life well into the 2020's.

Keywords: Mars Reconnaissance Orbiter, Mars Exploration, Mars

Acronyms

ADR	Adaptive Data Rates
AS	All-Stellar
C&DH	Command & Data Handling
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars
CTX	Context Imager
DSN	Deep Space Network
EDL	Entry, Descent, & Landing
EDM	EDL Demonstration Module
EM	Extended Mission
EMI	Electromagnetic Interference
EOD	End of Discharge
ESA	European Space Agency
EZ	Exploration Zone
HiRISE	High Resolution Imaging Science Experiment
IMU	Inertial Measurement Unit
ITL	Integrated Target List
JPL	Jet Propulsion Laboratory
LIM	Laser Intensity Monitor
LMST	Local Mean Solar Time
LTST	Local True Solar Time
MARCI	Mars Color Imager
MCS	Mars Climate Sounder
MEP	Mars Exploration Program
MER	Mars Exploration Rover
MGS	Mars Global Surveyor
MRO	Mars Reconnaissance Orbiter
MSL	Mars Science Laboratory
NASA	National Aeronautics & Space Administration
OTM	Orbital Trim Maneuver
PSP	Primary Science Phase
RQM	Relay Quiet Mode
RSL	Recurring Slope Lineae
SHARAD	Shallow Subsurface Radar
SNR	Signal-to-Noise
WAC	MGS Wide Angle Camera
Tb	Terabits
TES	Thermal Emission Spectrometer
UHF	Ultra High Frequency

1. Introduction

The Mars Reconnaissance Orbiter (MRO) Project is a major element of the Mars Exploration Program (MEP). The MRO 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 atmospheric, surface, and subsurface observations. The mission has been granted multiple extensions in accordance with NASA's Senior Review Process. Now in its Fourth Extended Mission (EM4), MRO continues to carry out a program of scientific exploration and programmatic mission support.

1.1 Extended Mission Objectives

MRO is a dual-mode mission having both scientific and programmatic support objectives [2]. The four major scientific goals of EM4 (October 2016 – September 2018) are focused on a "Mars in Transition" theme. Those scientific goals are to:

- Understand Environmental Transitions and Habitability of Ancient Mars;
- Understand Ices, Volcanism, and Climate of Amazonian Mars;
- Understand Surface Changes and its Implications for a Modern Dynamic Mars; and
- Understand Atmospheric and Polar Processes of a Modern Dynamic Mars.

In addition to its scientific objectives, MRO will continue its mission support to active and future missions. The primary programmatic support objectives include:

- UHF surface relay link for landed vehicles;
- Recording of critical event telemetry for entry, descent, and landing (EDL) vehicles;
- Landing site reconnaissance;
- Support of mission surface operations; and the
- Delivery of environmental data to support mission design and EDL planning.

1.2 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 [3]: 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] to provide lower-resolution but wider field-of-view. In addition to the science payloads, spacecraft radiometric data are used to support gravity science studies.

Figure 1. Artist rendering of the MRO Spacecraft

1.3 Spacecraft Operability and Target Planning

The MRO spacecraft is normally oriented such that its payload elements remain nadir-pointed to Mars. Owing to its gimbaled 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˚ from nadir to enhance its targeting field-of-view, to produce stereo from separate view angles, or for higher signal-to-noise radar observations. Gimbaled 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 onboard flight software targeting module. The targeting module is provided a conflict-free list of observations and relay overflights produced by ground planning software and operations personnel. 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 period, MRO completes 12-13 orbits each day.

1.4 Extended Mission 4 Timeline

The overall mission timeline for EM4 is shown in Figure 2. It includes Mars seasons; global dust storm periods; the solar conjunction command moratorium period; spacecraft activities such as orbital trim maneuvers (OTMs) and CRISM limb scans; spacecraft roll limits; local mean solar time (LMST) drift and associated local true solar time (LTST). Such LMST drifts are generally to ensure coverage of other mission critical events. It also includes significant events from other missions: ExoMars EDM EDL; InSight launch, cruise, and EDL; ongoing MSL and MER-B surface operations; MAVEN operations and coordination opportunities with MAVEN Deep Dip campaigns. Predicted daily data volume estimates are also shown. During EM4, MRO will continue to be maintained in its nominal low altitude science orbit.

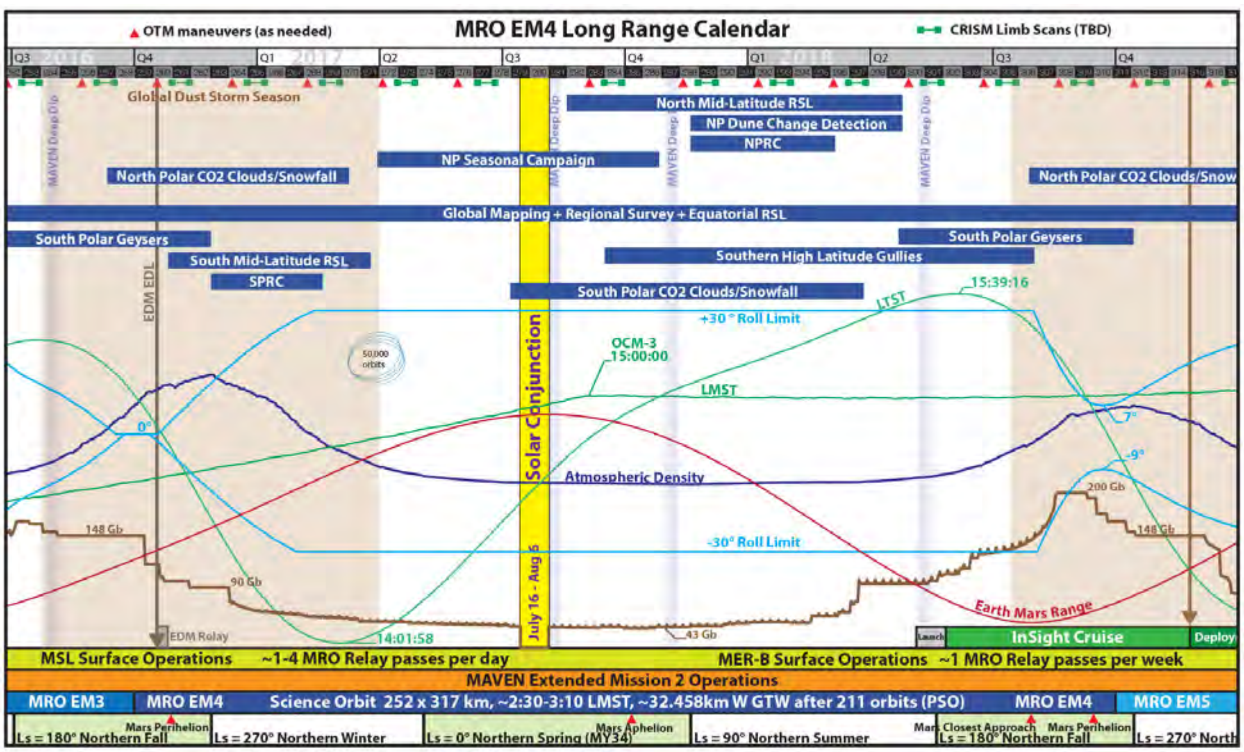

Figure 2. MRO Extended Mission 4 Timeline (July 2016 – December 2018)
(Top) Blue bars show approximate seasonal durations of EM4 activities.
(Bottom) Lines show spacecraft roll limits, LMST drift and associated LTST.

2. Selected Science Results

A key emphasis of MRO during its 4th Extended Mission (EM4) was to further understand change on the planet, early in its history, in recent geologic times and occurring even today. Indications of such change were detected in the 3rd Extended Mission and earlier mission phases [4] and are now being investigated more systematically. Of course, Mars has been "in transition" since its earliest days and change continues even today. The following highlights are organized around the goals of EM4.

2.1 Transitions in Ancient Environments

MRO data indicate that ancient environments on Mars did not change in a smooth progression from wet/neutral to dry/acidic. Compositional and morphological observations indicate that diverse environments may have come and gone, some repeatedly. Furthermore, there may have diverse environments occurring at the same time, with lakes in low-lying terrains and glaciated highlands. While all water-related environments have the potential for habitability, some are more conducive to life-as-we-know-it and some of those are more likely to have preserved biosignatures, presuming that the planet was once inhabited by life forms.

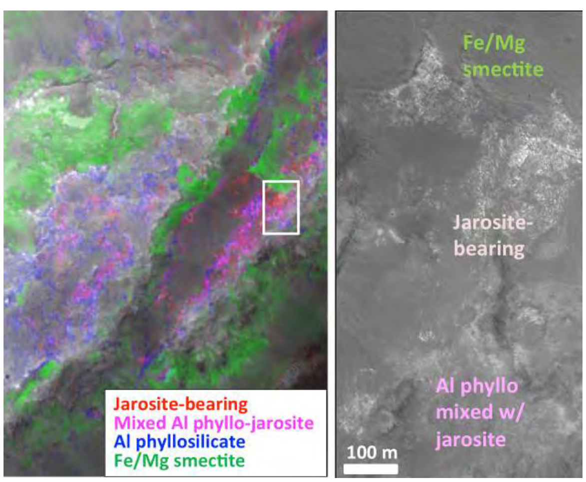

Figure 3. MRO CRISM mineral data show environmental transitions.
CRISM data shown in false color to indicate mineral class suggesting transitions from neutral pH (green) to acidic (blue, pink, red) environments. Left: CRISM mineral classes shown overlaid on a HiRISE image. Right: While box on the left is enlarged to show detail, including correlation with surface albedo and morphology. (CRISM / JUHAPL / JPL / NASA; HiRISE / U. Arizona / JPL / NASA)

Figure 3 shows evidence for different environments in close proximity, suggesting transitions from more to less habitable environments.

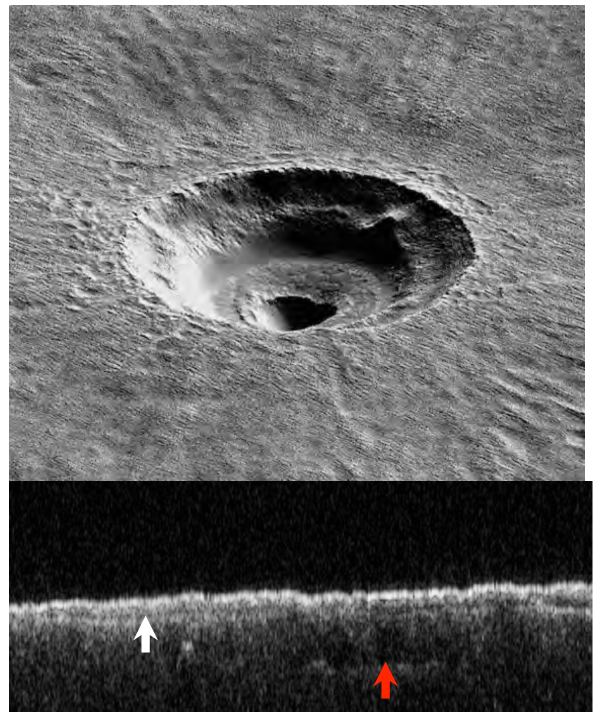

Figure 4. Icy plains revealed.
Terraced craters seen in HiRISE data (top) combined with SHARAD detected radar reflections from the base of ice layers (bottom; white, red arrows) point to massive, multiple layers of ice in Arcadia Planitia at high northern latitudes.

2.2 Mid-Latitude Ice and Ice Ages

MRO has reveal buried ices of water and carbon dioxide [5-6], evidence of geologically recent climate change. Continuing observations are exploring the three-dimensional structure of the polar caps [7-8] and the distribution of massive ice near the surface at high latitudes (Figure 4, [9-10]) and even exposed ice cliffs (Figure 5) on pole facing scarps. Additionally, the known distribution of very shallow ice (within 1-2 meters of the surface) has been extended by viewing new impact craters with bright, white floors, revealing nearly pure ice (Figure 6, [11]). Such ice might one day provide resources to humans exploring on the surface of Mars.

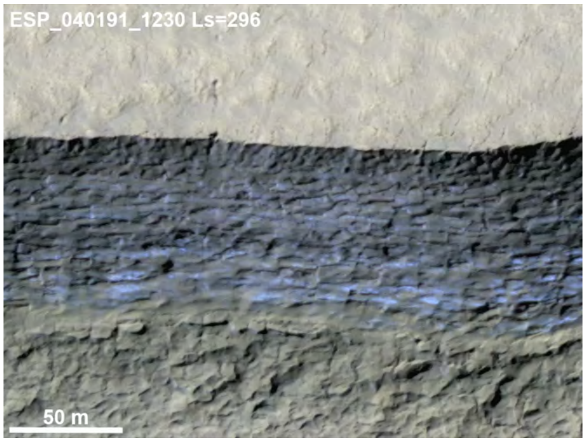

Figure 5. High latitude ice cliffs.
HiRISE color differences—and CRISM spectra confirm--that cliffs of ice are exposed in mid-latitude scarps. These scarps remain relatively "blue" even in late summer, long after seasonal frost has disappeared. (Dundas et al., paper submitted)

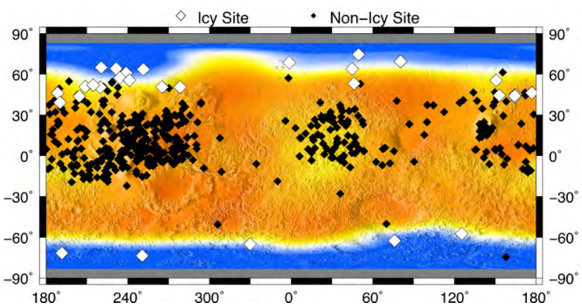

Figure 6. New icy craters identified.
New impact locations detected by MRO CTX and confirmed by MRO HiRISE are shown superimposed on a map of water-equivalent hydrogen from the Gamma Ray Spectrometer suite on Mars Odyssey (blue indicates the presence of near-surface ice). White diamonds indicate those icy-bottom craters, exposing shallow ice below the ~1m depth of regolith probed by Odyssey. New craters continue to be detected, adding to those previously published [11].

MRO continues to map out the volume of carbon dioxide ice buried in the south polar cap. Recent estimates of this volume are such that, if the buried CO_2 ice were ever sublimed into the atmosphere, it would double the present atmospheric pressure [12]. Such exchanges could occur on time scales of hundreds of thousands to a few million years. Water ice would also be affected by the driving changes in obliquity of the rotation pole and the precession and changing eccentricity of the orbit. The large volumes of mid-latitude ice and the internal layering of the polar caps—especially in the north—indicate multiple ice ages in the last very few million years or so (Figure 7). The most recent of these low-latitude ice ages may have ended just 370,000 years ago (Figure 7), the period when the topmost (youngest) ice layer of the north polar cap began to form [13].

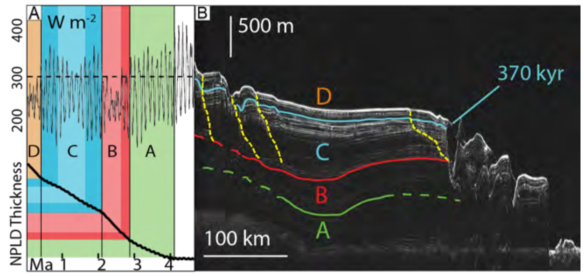

Figure 7. Obliquity driven ice ages and layers.
Right: SHARAD radar-grams with the darker zones interpreted as icy layers separated by dustier ice nonconformities which appear brighter in the radar data. **Left**: Polar insolation (W/m^2) calculated from obliquity variations for the last few million years. Note that the insolation falls below the dashed line for those epochs when water ice was accumulating at the north pole (including at present). [13].

The heavy black line in Figure 7 shows the accumulated thickness of the north polar cap, nearly a mile thick at present, indicating that the cap has net growth through these obliquity cycles despite periodic sublimation of the water ice, leading to dust accumulation on the cap surface while water is transferred to lower latitudes in a Martian ice age [13].

2.3 Surface Changes on Modern Mars

MRO has been in orbit long enough that, given its very high spatial resolution camera, it has been able to detect several categories of surface change. For instance, MRO has provided observational evidence that proves sand dunes do move and change on Mars today [14]; they are not just fossilized remnants of some past climate.

At high latitudes CO_2 snow and frost fall and form in the autumn and winter seasons to form a seasonal polar cap that then begins to sublime away in spring. MRO has previously shown that the observations support the hypothesis that the winter CO_2 can form a transparent glaze ice that sublimes from below when sunlight again illuminates the polar latitudes. The volatilization of the CO_2 forms a jetting action that can move dust and sand, blocks of CO_2 can slide down dunes and other slopes—in effect, CO_2 becomes the volatile (not water) driving surface change.

MRO has never been fortunate enough to capture one of these jetting events [15] ("geysers"), but HiRISE has seen evidence of surface cracks [16-17] that elongate from year to year as the seasonal CO_2 escapes back into the atmosphere (Figure 8).

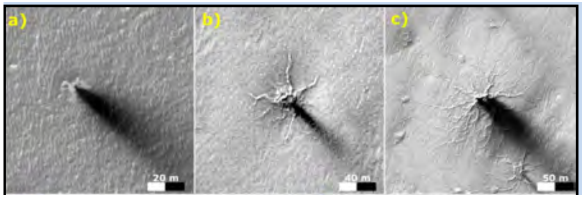

Figure 8. Springtime sublimation of CO_2. Shown are the various stages of development (not at the same site) of erosional ("araneiform") structures in the south polar region of Mars. [17]

Other phenomena at the limit of our current orbital remote sensing are the enigmatic Recurring Slope Lineae (RSL; Figure 9). During the warmer times of years, long and narrow (a few meters in width at most) dark streaks are observed to form on steep crater slopes or canyon walls and to elongate down slope, only to fade away during cooler periods. [18] The cycle then repeats in the same location in subsequent Mars years.

This observed morphology is suggestive of brine seeps: Brines are required if the water is to remain liquid at typical Mars temperatures; perchlorate salts in particular can depress freezing points by 80K or so. "Seeps" seem a better descriptor as the amount of water involved appears to be very small. However, the exact mechanism and source of the water are not understood.

On their lowest reaches, the RSL slopes estimated from Digital Terrain Maps produced from HiRISE stereo images appear to be at the angle of response for granular material (between 28˚ and 35˚), suggesting dry avalanching [19]. The upper reaches extend downslope from bedrock outcrops, often associated with small channels, and hundreds of them form in rare locations. Sometimes the RSL reach all the way to a crater rim, arguing against ground water flow. However, deliquescence of atmospheric vapor seems inadequate given the very small amounts that the atmosphere currently holds and the restricted extent of RSL formation. And yet it is difficult to imagine another mechanism, other than some kind of "wetting" action, that can account for their seasonal timing.

RSL appear most frequently in the southern spring and summer from 48 degrees to 32 degrees south latitude, favoring equator-facing slopes. Due to the current obliquity and phase of perihelion, this season and latitude band have the warmest temperatures on the planet. Another area of RSL activity is Valles Marineris [20], the great rift system near the equator. The RSL in some near-equatorial craters act as an annual sundial, forming on the sun-facing slopes and fading as the subsolar latitude moves back and forth across the tropics. Laboratory experiments are providing new insights into the RSL triggering mechanism. Meanwhile, MRO is working to further identify their presence and thus to constrain the environmental conditions under which they form. For now, the controversy about the nature—and implications—of RSL continue.

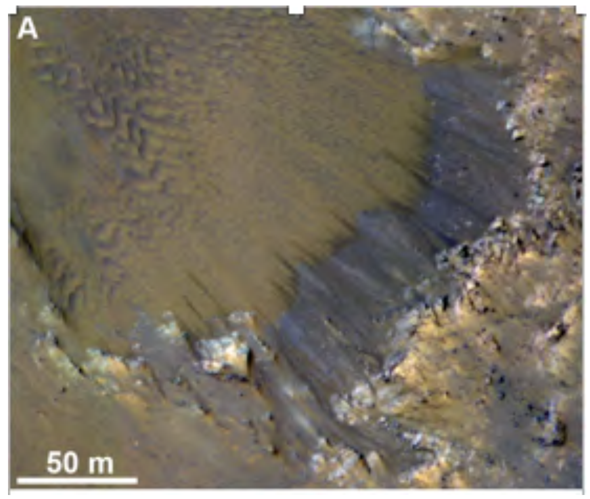

Figure 9. Recurring Slope Lineae (RSL). (HiRISE / U. Arizona / JPL / NASA)

2.4 Atmospheric & Polar Processes on Modern Mars

MRO MARCI, MCS and CRISM directly measure atmospheric state fields and processes on interannual, seasonal, day-to-day and diurnally varying time scales. These are the predominant time-scales of variation in terms of atmospheric opacity (water and carbon dioxide ice clouds and dust hazes) and frequency of atmospheric storms. Adding the 5 full Mars years of MRO data taken by MARCI and MCS to the Mars Global Surveyor Wide-Angle Camera (WAC) and Thermal Emission Spectrometer (TES) respectively provides nearly a decade of Mars years of daily global maps of the Mars atmosphere in the early afternoon and of atmospheric temperature and dust profiles.

Local dust storms occur in every season on Mars and can appear anywhere on the planet, but there are particular zones where storms travel more frequently [21] (Figure 10). Most local dust storms originate in the jet streams located near the edges of the polar ice caps, driven by the strong temperature/pressure gradients there. In the northern hemisphere, the large-scale topography ducts many local dust storms down 3 major "storm tracks" in the western boundary currents of Acidalia/Chryse, Utopia/Isidis, and Arcadia/

Amazonis. Sometimes these storms bloom into large-scale events, particularly those that go down the Acidalia/Chryse track, crossing the equator before being caught in the subtropical westerlies of the southern hemisphere. Not all such storms "bloom"; many just dissipate away. The processes that differentiate such events is not known.

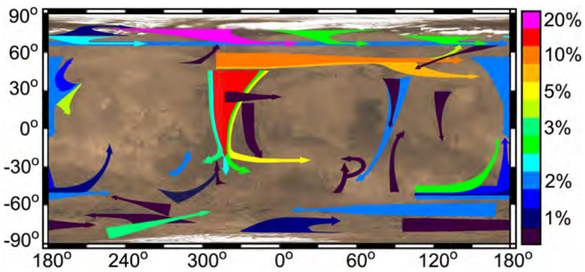

Figure 10. Local Dust Storm Pathways.
Color indicates % of the total of local dust storms occurring on Mars in Mars Years 23-32 (1997-2015) moving in different tracks and zones. [21] The global composite is based on MGS WAC and MRO MARCI daily global maps. (MSSS / JPL / NASA)

In looking at the TES and MCS record for those years without planet-encircling dust events, a pattern for the regional storms appears (Figure 11) [22]. An early season storm (A) occurs in about half of those years and a late season event (C) occurs in most of those years.

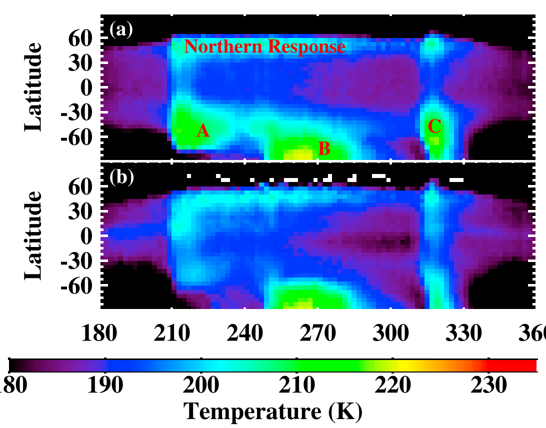

Figure 11. Regional Dust Storm Signatures in MCS Temperature Data
Day (a) and night (b) temperatures at ~25 km altitude, zonally averaged and binned in 2˚ of areocentric longitude L_s, for southern spring and summer (L_s 180-360˚) in Mars Year 31. [22]
(MCS / Caltech / JPL / NASA)

The mid-season (near-solstice) events (B) occur in all years, although the lead-in conditions differ significantly from year to year. For all three classes the regional events vary from year to year in intensity (i.e., warming of the mid-level atmosphere). Note that the southern hemisphere warming is due to the direct solar heating of a dusty atmosphere, while the northern response is due to the adiabatic warming of sinking air which forms the down-welling branch of a vast cross-equatorial Hadley-type circulation. MRO continues to add to this long record of the dust cycle as its mission is extended.

As was noted in earlier sections, the polar regions exhibit major control on the volatile cycles of water and carbon dioxide. From the atmospheric side, a long-standing question has been whether it snows on Mars; i.e., does CO_2 condense into ice that falls onto the polar surface, as opposed to freezing as frost there.

MCS campaigns quantifying snowfall and emissivity changes are elucidating the extent of CO_2 ice cloud cover over both poles and of changes in surface emissivity, which will further affect the radiation balance at the surface, both during contact freezing and springtime sublimation. Figure 12 shows early results for the south polar region. Many of the indicated snowfalls occur near topographic features (e.g., the Mountains of Mitchell), suggesting orographically induced precipitation. The contribution to overall surface CO2 mass is significant [23].

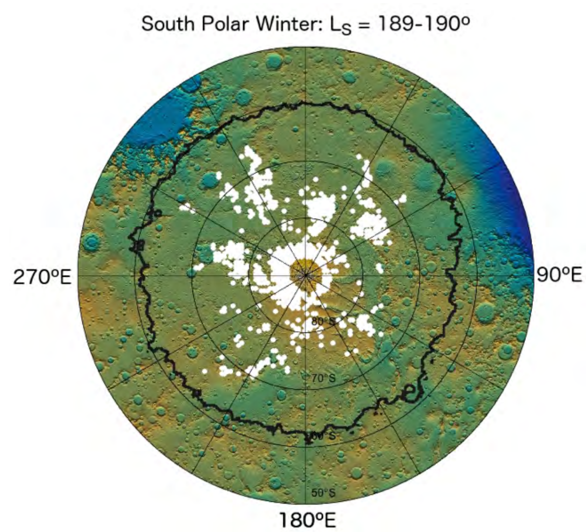

Figure 12. CO_2 snowfall very early in southern spring.
White dots indicate the locations of 2 sols of CO_2 snowfall recorded by MCS within the extended seasonal cap (heavy black line). [23]
(MCS / Caltech / JPL / NASA)

2.5 Science Data Archiving

The MRO science investigation teams continue to deliver all standard and many special data products to the Planetary Data System within 6-9 months of data acquisition. Most teams are delivering standard products within 3-6 months of acquisition. The one exception to this was an interruption in delivery of SHARAD data products for an extended period, but this is being remedied and will be caught up by the end of the year.

3. Extended Mission Programmatic Support Functions

NASA has tasked the Mars Reconnaissance Orbiter Project to provide essential mission support to designated ongoing and future Mars missions. These tasks have three principal goals:

- To substantially enhance the scientific return from surface missions, principally by providing a lower power relay path for the landers and rovers to return surface mission data;
- To identify and characterize specific landing sites for future surface missions; and
- To lower the risk of losing or damaging highly valuable space assets by collecting critical event EDL data for post-flight performance analysis and providing environmental information to support surface operations.

Every MRO payload element provides some measure of programmatic support. Table 1 aligns the payload elements with their contributing programmatic functions and notes the major campaigns/missions that MRO has either supported or is currently supporting.

Table 1. Programmatic Functions

Programmatic Function	HiRISE	CRISM	CTX	SHARAD	MCS	MARCI	Electra
Landing Site Reconnaissance	X	X	X	X			
Pre-EDL Atmospheric Study					X	X	
EDL (Critical Event Coverage)	X		X				X
Post-EDL Assessment	X		X		X		X
Traverse/Operations Support	X	X	X			X	
Relay (Active): MER-B, MSL							X
Relay (Future): InSight, Mars 2020, ExoMars 2020, Red Dragon							X

Campaigns/Mission Supported:

Phoenix*	MER-A*	MER-B	MSL	InSight	Red Dragon
ExoMars	EDM*	Mars 2020	ExoMars 2020	Human Exploration Zones (EZs)	

**Mission Support Completed*

3.1 UHF Relay

Relay involves sending commands to, and returning data from, landed spacecraft. This is accomplished via the Electra UHF transceiver. Relay data return represents less than 2% of the total data return by MRO and is limited by the performance of the UHF link and overflight durations.

In EM4 MRO regularly relays with the Mars Science Laboratory (MSL) rover *Curiosity* and the Mars Exploration Rover (MER-B) *Opportunity*. MRO is considered the prime relay link for *Curiosity* and typically provides 14 relay passes per week, returning an average of 225 Mbits of data per pass using an adaptive data rate (ADR) scheme. Approximately 75% of all of MSL's science data has been relayed to Earth by MRO. To ensure support of the MER-B rover in the event the *Odyssey* orbiter is not available, MRO provides *Opportunity* ~2-3 relay passes per week, returning an average of 50 Mbits of data per pass using a fixed data rate scheme. Table 2 summarizes MRO relay support for all missions.

3.2 Relay with the ESA ExoMars Schiaparelli EDL Demonstration Module (EDM)

MRO was one of several Mars orbiters that planned to provide surface relay capability for the ESA Schiaparelli EDL Demonstration Module (EDM). The MRO primary support period was scheduled for the first 4-Sols immediately after EDM landing (10/19/2017) and, if the battery-powered lander exceeded its lifetime expectations, the MRO relay support period could be extended to 14-Sols after EDM landing.

Table 2. MRO Relay Data Volume (July 28, 2017)

Lander	Total Passes	Average Volume/Pass	Total Return Volume
PHX	240	39.4 Mbits	9.4 Gbits
MER-A	24	45.6 Mbits	1.1 Gbits
MER-B	422	46.0 Mbits	19.4 Gbits
MSL	3276	224.9 Mbits*	726.6 Gbits
EDM	5**	0 Mbits	0 Gbits
Total	3967	---	756.6 Gbits

* Nominal ADR passes
** Due to EDM failure, relay links with the lander on the surface were never established.

To ensure an initial set of robust relay passes, MRO was targeted to a specific set of conditions for the third EDM overflight. These conditions included an overflight time (tolerance ±5 min), a pass elevation angle constraint (greater than 30 deg), and a pass duration constraint (greater than 10 minutes) [24]. Additionally, MRO powered off several of its science instruments during the primary support period in order to reduce electromagnetic interference and thereby enhance UHF relay link performance.

Given MRO's imaging capabilities, MRO was also requested to image the EDM landing site post-EDL. Only three EDM overflights satisfied the imaging lighting (daylight) and spacecraft roll constraints and all three were scheduled for CTX and HiRISE imaging. The first imaging opportunity targeted the nominal EDM landing location. The second and third would be retargeted based on the results acquired from the first imaging. The timeline for the MRO EDM support plan is shown in Figure 13. Down arrows indicate the planned EDM relay passes; green rectangles indicate imaging opportunities.

Unfortunately, relay links with EDM were never established after the landing event. Prior to ending EDM relay support, MRO supported five prox-1 relay overflights and one open loop recording. No data were ever received from EDM on any of the prox-1 passes. For the open loop overflight, a 3-Gbit open loop recording of the UHF spectrum was collected and analyzed, but again, no signal from EDM could be found in that product. Fortunately, some EDL data were received through the Trace Gas Orbiter, which had carried the EDM to Mars. Additional discussion on relay support for the Schiaparelli lander can be in reference [25].

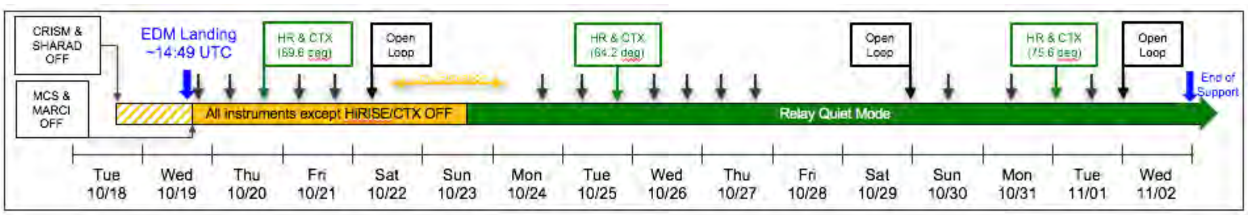

Figure 13. EDM Support Timeline – Oct 2016

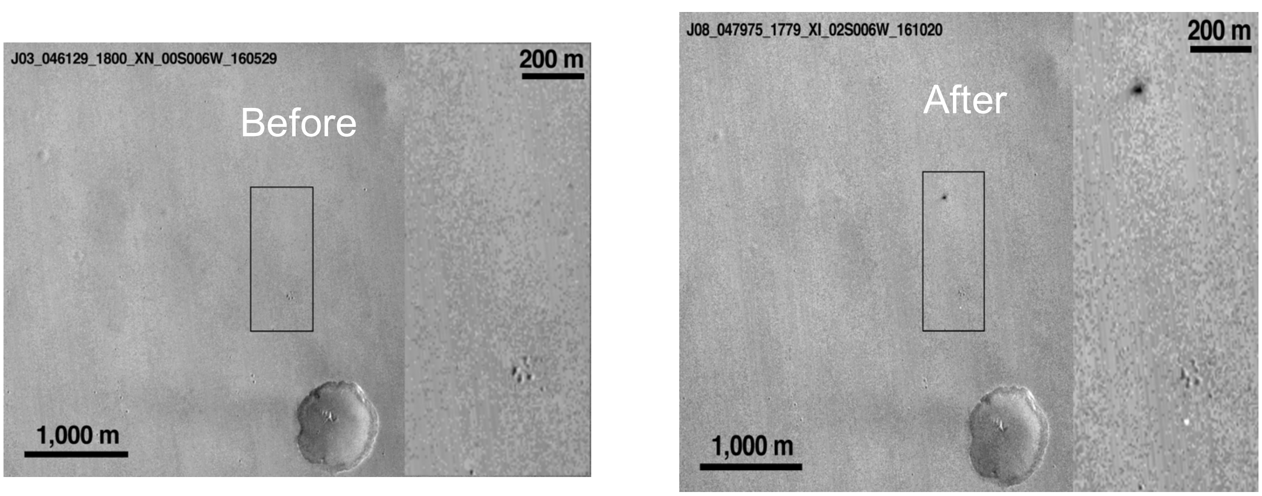

Figure 14. Before (May 2016) / After (Oct 2016) CTX Images of the Schiaparelli Landing Site
(CTX / MSSS / JPL / NASA)

With its unique imaging capabilities, MRO was able to provide ExoMars personnel a visual perspective of the EDM landing area. CTX found the lander and parachute within the first image. Subsequent images were re-targeted so that all components were in the smaller, but higher resolution HiRISE frame and the parachute and lander were within the 1.5-km wide color strip (Figure 15).

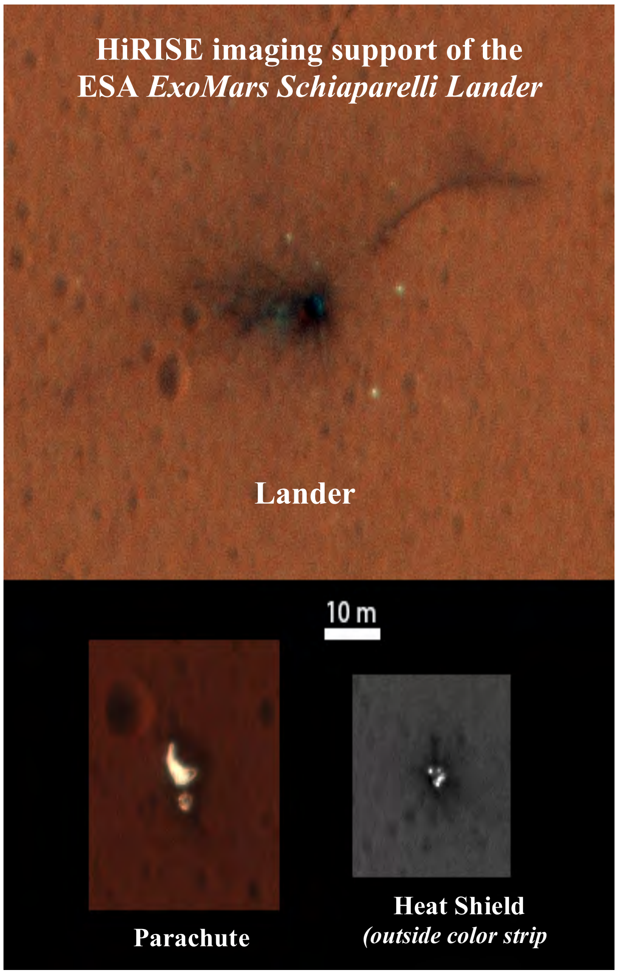

Figure 15. HiRISE Color Images of Schiaparelli Landing Site – Oct 2016
(HiRISE / U. Arizona / JPL /NASA)

3.3 Landing Site Reconnaissance

Landing site reconnaissance includes the identification, characterization, and certification of potential landing sites for future landed missions. Identification means that the site contains geologic units at which compelling in situ measurements needed to achieve the landed mission's goals can be made. Characterization means that the distribution of key materials, their stratigraphic relationships, and those exposures to the surface that could provide access at spatial scales not resolvable from orbit – thus, the scientific potential of the site for future discovery. Certification means that the site is acceptably free of hazards for the landing system. This entails high resolution imaging to determine local slopes and to detect surface hazards (e,g, rocks, pits, etc.).

MRO uses a priority and allocation scheme in its scheduling of relay and targeted observations. Relay receives first priority in the scheduling process. Typically, landing site observations have a high priority but are limited in number each planning cycle. This restriction enables MRO's science teams to acquire the data sets necessary for their scientific investigations, thus sharing the observing timeline between the programmatic and scientific objectives.

In EM4, MRO completed its site reconnaissance of a site in Elysium Planitia for the 2018 InSight Mission. This is visually illustrated in Figure 16 with HiRISE imaging strips superimposed over the InSight landing ellipse. The HiRISE images were acquired over many orbital passes. MRO reconnaissance data has also supported the downselect of the NASA Mars 2020 mission to three sites: Jezero Crater, NE Syrtis, and Columbia Hills in Gusev Crater and the downselect of the ESA ExoMars 2020 mission to two sites: Oxia Planum and Mawrth Vallis. In addition to these missions, MRO supports several future landing site campaigns, including future Human Exploration Zones (EZ) and some areas that are not yet assigned to any specific mission. Figure 17 shows the landing locations of MER-B and MSL as well as candidate NASA and ESA landings sites for their respective 2020 missions. Further discussion on MRO's landing site reconnaissance capabilities and methods can be found in reference [26].

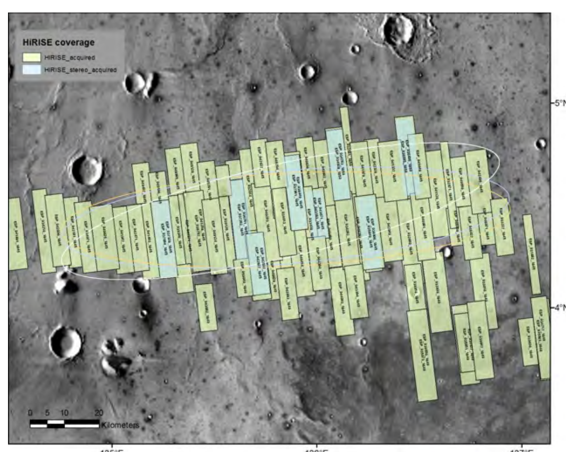

Figure 16. InSight Landing Ellipse with HiRISE Imaging Strips Superimposed – Apr 2017

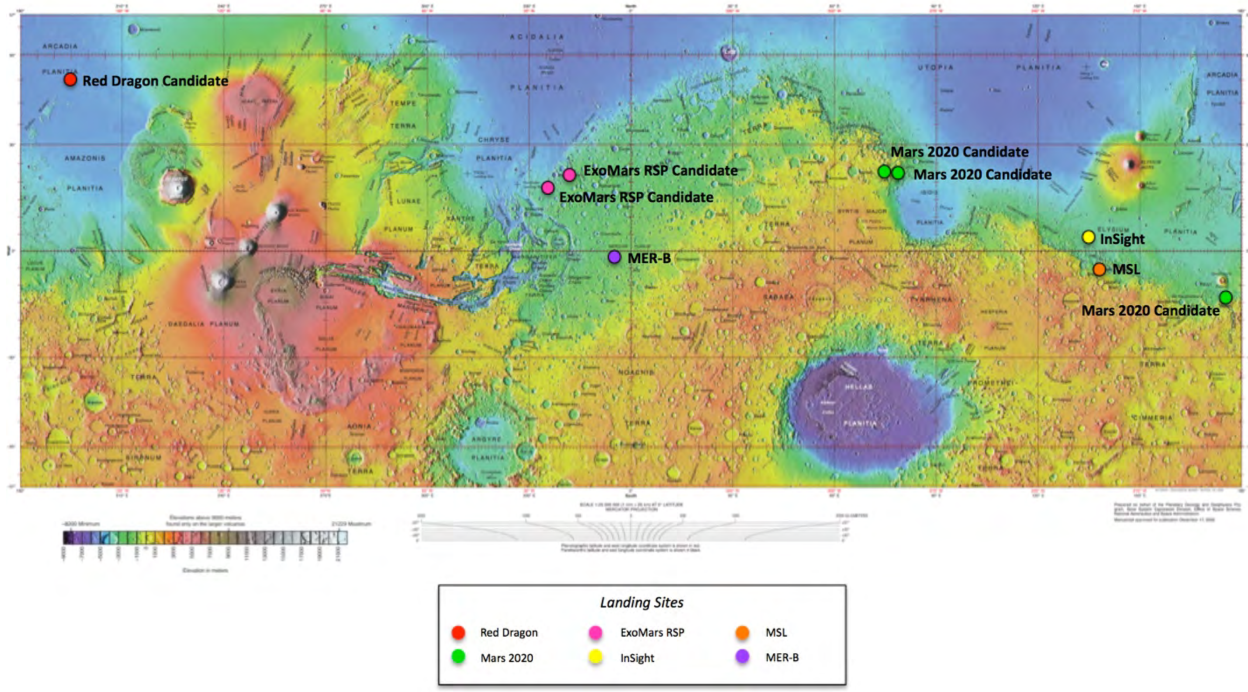

Figure 17. Current and Candidate Landing Sites

3.4 Environmental Data to support Surface Operations and Mission Design

MCS and MARCI provide atmospheric structure and change characterization, including data for model validation to assist design and simulation of flight performance. These data are a significant aid to EDL planners; particularly, when acquired at the appropriate Mars season prior to or in the weeks leading up to the planned event. HiRISE, CTX, and CRISM data aid the traverse planning of *Curiosity* and *Opportunity* by identifying safe paths of travel and areas of dangerous terrain. This allows for efficient and scientifically productive rover operations.

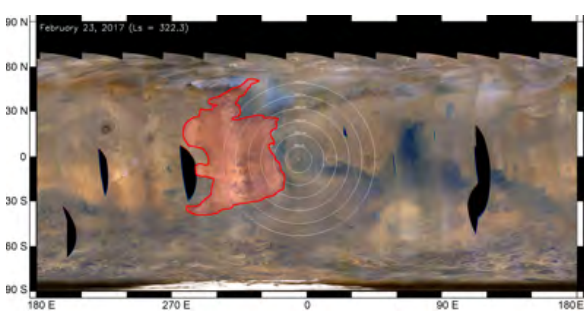

Figure 18. Regional Dust Storm relative (circles) to MER-B (Opportunity) – Feb 2017
(MARCI Daily Global Map—MSSS/JPL/NASA)

Atmospheric dust storm alerts are provided to the solar-powered Opportunity in order to better support rover power management by preventing unexpected power shortages. The red area/outline shown in Figure 18 shows the extent of a regional dust storm observed by MARCI in February 2017. Concentric circles show the distance from the solar-powered Opportunity rover which was distant enough that it was largely unaffected by this event. Had the storm been closer, the rover would have gone into a power conservative sleep.

4. Flight and Mission Operations Challenges

Now entering its 11th year of orbital 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 [27-28] 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 behaviours at times, but the flight team has been able to quickly recover the spacecraft and restore normal operations. Instrument produced electromagnetic interference (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 requirements.

4.1 Inertial Measurement Units – All-Stellar Attitude Determination

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 normal operating 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 surface mission of the Mars 2020 rover in 2021-2024. 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 has developed an All-Stellar (AS) attitude determination mode that uses the orbiter's star trackers, allowing spacecraft operations to continue without the IMUs powered.

On April 19, 2017, the all-stellar capability was installed on-board the spacecraft as a patch to the existing flight software code base. To assess the performance of the all-stellar algorithm, a series of flight demonstration activities will be performed. For the first set of demos, which were recently completed, the spacecraft was operated in a "dual" attitude determination mode. In dual-mode, the normal gyro-driven attitude determination mode remains in control of the vehicle while the all-stellar algorithm computed attitude solutions. The computed solutions have been downlinked to ACS engineers for detailed analysis. Initial results show good agreement between gyro based control and the new AS algorithm.

After the 2017 solar conjunction period, the all-stellar algorithm will be allowed to fully control the spacecraft in a second set of flight demonstrations. For the first three of these, the IMU will be left on and AS will be active in the control loop for increasing periods of time (initially for a period of one hour working up to a period of six orbits). For the last flight demo, the IMU will be turned off and all-stellar will be allowed to control the spacecraft in normal operational mode for one week. This last test is of particular importance because it will determine if AS driven control can be used to acquire un-smeared very-high-resolution HiRISE images. Once the flight demos are completed and the performance results fully assessed, the all-stellar capability will be certified for normal operational use.

4.2 Battery Management (End of Discharge Voltage)

Due to its low altitude, the MRO spacecraft experiences 40 minutes of solar eclipse every orbit. Two nickel hydrogen batteries provide power for the spacecraft during the eclipse periods. Since the start of orbital operations, the batteries have experienced steadily decreasing End of Discharge (EOD) voltages. The EOD voltage is reached at the end of each eclipse period, when the batteries are at their lowest state of charge for the orbit. This decrease is as expected for the design of the batteries and the orbital environment, and while overall performance has been better than originally predicted, the batteries have been steadily losing capacity, while internal impedances have been growing. Eventually the batteries will reach a point in their voltage curves at which the voltage will drop off rapidly and the spacecraft will experience an undervoltage fault condition. For this reason, battery operations are designed to maintain an EOD voltage of 25.3V at all points in the Mars year. Using the current spacecraft battery loading scheme, the batteries could reach their EOD voltage limits in 2019. To prevent this from happening, the MRO Project has developed a "phased" battery management/conservation plan. The first phase of this plan was to shift the heater loads of select spacecraft components to sunlight, thereby reducing battery discharge during eclipse. To prevent these components from becoming too cold during eclipse, they are pre-heated during the sunlit portion of the orbit. This first phase was implemented in early 2017 through sequencing and then later by a new spacecraft eclipse block. The second phase of the battery management plan calls for shifting payload (instrument) loads to sunlight. This part of the plan is currently in implementation with the primary action the shifting of HiRISE warm-up images to sunlight. Still under study is an option to further reduce battery depth of discharge by changing HiRISE heater setpoints. If the two phases described above are not sufficient, a third phase of the plan could be implemented. This would require MRO to shift its orbital node to later local mean solar times. Later LMSTs have shorter eclipse durations. This option is extremely undesirable for MRO science because it will have a significant impact on instrument signal-to-noise (SNR). Currently the third phase of the plan is not expected to be needed. Current power analysis shows that by implementing the first two phases, MRO battery life can be extended to at least 2024.

4.3 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 the Electra telecommunications radio operates. The 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 undesireable 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 MSL Project has agreed to allow CRISM to observe on the same UHF frequency used for the Curiosity rover. On that frequency, the relay losses due to CRISM EMI are relatively small (5% to 8%) and in many cases, the losses are in family with the normal pass to pass variations.

4.4 Expanding 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 during a pass (like Phoenix), 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 has been expanded again. The proximity of *InSight's* Elsium 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 surface vehicles in a matter of minutes. Rather than being restricted to support one mission or the other, MRO has developed a "split-pass relay" capability that allows for non-overlapping UHF communications to both vehicles on the same overflight. Split-pass relay represents a significant update to the *MRO* relay system and has impacted many different project elements: mission planning, science planning, spacecraft constraint checking, plus a new series of spacecraft blocks that implement the capability onboard. During the last quarter of 2016, these new relay blocks completed their development and underwent rigorous testing. They were uplinked to the spacecraft as part of a relay block library update in December 2016. In addition to the *MRO* impacts, MaROS, the Mars relay ground planning interface, has had to make major updates to support this new capability.

Over the course of the MRO mission, relay capability has been significantly expanded several times. This has been done without a need to change 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 full design and development cycles including rigorous functional and regression testing prior to spacecraft upload.

5. Summary

The Mars Reconnaissance Orbiter is about to enter its 12th year of flight. No other spacecraft, currently flying or in development, has the scientific and programmatic capabilities of MRO. Due to this dual-mode nature, the MRO spacecraft has become the workhorse of the Mars Exploration Program. Overall, the spacecraft has performed superbly since it has been on station in its primary science orbit.

MRO's powerful suite of science instruments continues to unveil Mars in unprecedented detail. Remarkably, the MRO instruments retain their essential capabilities, even as they are now in their 11th year of operation in Mars orbit. The MRO science investigations have shown 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.

Notable science metrics (as of July 28, 2017) include:

• Over 308 Terabits of Science Data returned
• Acquisition of over 250,000 targeted images, and image equivalents:
– 99.2% of the planet imaged at 6 m/pixel (CTX)
– 2.9% imaged at 30 cm/pixel (HiRISE)
– 85% of planet covered - multispectral (72 channels) low-opacity IR (CRISM)
– Daily Global Maps (MARCI) for ~5.5 Mars years (49,645 images)
– Atmospheric Profiling (MCS) on 13 orbits per day for ~5.7 Mars years (153.8 million soundings)
– Shallow, Subsurface Soundings (SHARAD) covering nearly half the planet (~21,000 observing strips)

In addition to its scientific 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. MRO's UHF relay capabilities are a critical component of an evolving international Mars campaign. Preparations are nearly complete for the new demands that the InSight Lander will place on MRO in 2018. MRO has already set itself on course for InSight EDL with a special orbital adjustment maneuver performed in March 2017 [29].

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. With large fuel reserves (200 kg) and significant subsystem life and redundancy remaining, the MRO spacecraft is expected to stay on-orbit as the flagship of the Mars Exploration Program for many years to come.

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