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An overview of the Mars Reconnaissance Orbiter (MRO) science mission

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[1] The Mars Reconnaissance Orbiter (MRO) is the latest addition to the suite of missions on or orbiting Mars as part of the NASA Mars Exploration Program. Launched on 12 August 2005, the orbiter successfully entered Mars orbit on 10 March 2006 and finished aerobraking on 30 August 2006. Now in its near-polar, near-circular, low-altitude (~300 km), 3 p.m. orbit, the spacecraft is operating its payload of six scientific instruments throughout a one-Mars-year Primary Science Phase (PSP) of global mapping, regional survey, and targeted observations. Eight scientific investigations were chosen for MRO, two of which use either the spacecraft accelerometers or tracking of the spacecraft telecom signal to acquire data needed for analysis. Six instruments, including three imaging systems, a visible-near infrared spectrometer, a shallow-probing subsurface radar, and a thermal-infrared profiler, were selected to complement and extend the capabilities of current working spacecraft at Mars. Whether observing the atmosphere, surface, or subsurface, the MRO instruments are designed to achieve significantly higher resolution while maintaining coverage comparable to the current best observations. The requirements to return higher-resolution data, to target routinely from a low-altitude orbit, and to operate a complex suite of instruments were major challenges successfully met in the design and build of the spacecraft, as well as by the mission design. Calibration activities during the seven-month cruise to Mars and limited payload operations during a three-day checkout prior to the start of aerobraking demonstrated, where possible, that the spacecraft and payload still had the functions critical to the science mission. Two critical events, the deployment of the SHARAD radar antenna and the opening of the CRISM telescope cover, were successfully accomplished in September 2006. Normal data collection began 7 November 2006 after solar conjunction. As part of its science mission, MRO will also aid identification and characterization of the most promising sites for future landed missions, both in terms of safety and in terms of the scientific potential for future discovery. Ultimately, MRO data will advance our understanding of how Mars has evolved and by which processes that change occurs, all within a framework of identifying the presence, extent, and role of water in shaping the planet's climate over time.

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1. Mission Rationale

[2] The Mars Exploration Program (MEP), conducted by the National Aeronautics and Space Administration (NASA), is a sustained series of missions to Mars, each of which provides important scientific return as part of a systematic exploration of that planet. The scientific objectives of the MEP, as recommended by the scientific community through the various groups advising NASA [e.g., *Space Studies Board* (*SSB*), 1996, 2003; *Greeley*, 2001], are as follows:

[3] 1. Search for evidence of past or present life.

[4] 2. Understand the climate and volatile history of Mars.

[5] 3. Understand geological processes and their role in shaping the surface and subsurface.

[6] 4. Assess the nature and inventory of resources on Mars in preparation for human exploration.

[7] The first of these goals addresses the overarching question of whether life ever developed on Mars; the last directly anticipates human missions to Mars as articulated in the National Vision for Space [*NASA*, 2004]. The climatic and geological objectives are fundamental to understanding the present planet and its evolution, thereby addressing

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basic questions of planetary formation and evolution with respect to the solar system and to planetary systems elsewhere in the universe. These processes and their results also provide the physical and geochemical context in which life may or may not develop.

[8] All these goals are linked by the common thread of the history and present role of water on Mars. This is because water is (1) essential to the development of life as we know it; (2) a key component in the present Martian climate; (3) a critical agent in the evolution of its atmosphere, surface, and subsurface; and (4) a vital resource for future explorers on Mars.

[9] The most recent addition to the MEP has been the development and launch on 12 August 2005 of the Mars Reconnaissance Orbiter. Eight scientific investigations were selected for this mission. Of the eight, six provide scientific instruments while two utilize spacecraft hardware to make primary measurements for their science investigations. The orbiter, meaning the spacecraft and scientific payload together, completed its aerobraking phase on 30 August and then transitioned to a primary science phase expected to last nearly two Earth years (November 2006 to November 2008). This paper provides an overview of the mission in terms of its scientific objectives, its mission phases and highlights of the capabilities and goals of the science investigations. The investigations themselves are defined in greater detail in the accompanying papers of this special section.

2. MRO Mission Objectives

[10] In the fall of 2000, NASA Headquarters organized a Science Definition Team (SDT) to develop the requirements for a new orbiter mission to Mars to be launched in August 2005. Working with a concept based on an earlier study of a Mars Surveyor Orbiter, the SDT made specific recommendations to NASA regarding the scientific goals and needed capabilities for the new mission, consistent with the NASA MEP "Follow the Water" theme. These goals and capabilities were developed in the context of, and were linked to, priorities established by the NASA advisory groups, particularly the scientific goals, objectives, investigations and priorities developed by what is now known as the Mars Exploration Program Analysis Group [*Greeley*, 2001] (see the update by *Grant* [2006]).

[11] Following delivery of the SDT Report in early 2001 [*Zurek*, 2001], NASA moved forward through four major actions. First, NASA Headquarters released in June 2001 an Announcement of Opportunity (AO) for the flight of instruments on MRO [*NASA*, 2001].

[12] Second, NASA moved to address the recommended climate objectives by reselecting for flight on MRO two investigations lost in 1999 when the Mars Climate Orbiter burned up during orbit insertion at Mars.

[13] Third, in an effort to pursue the subsurface exploration objectives within the projected mission resource cap, NASA and the Italian Space Agency (Agenzio Spaziale Italiana, ASI) agreed that ASI would provide a subsurface profiling radar for Mars, complementary to the multiband radar then being built jointly by NASA and ASI and now successfully flown on Mars Express. ASI released its own Announcement of Opportunity to select the radar investigation that it would fund, while NASA solicited participation by U.S. scientists (including a Deputy Team Leader) through the MRO AO.

[14] Finally, NASA directed the Jet Propulsion Laboratory to proceed with a Request for Proposals (RFP) for the spacecraft itself in parallel with the instrument selection through the AO process. Proposals for the spacecraft were received from several aerospace contractors in June 2001. In September 2001, JPL announced the selection of Lockheed Martin Astronautics (now Lockheed Martin Space Systems), Denver, Colorado, as the prime contractor for the MRO spacecraft.

2.1. Science Objectives

[15] In the summer of 2002 NASA formally established science objectives for the MRO mission. These objectives were essentially those articulated in the MRO AO with modest changes reflecting the actual payload selection in response to the AO and the final agreement on the radar to be provided by Italy. These scientific objectives, all supporting the NASA MEP "Follow the Water" theme, are listed below.

2.1.1. Present Climate

[16] In order to understand processes of present and past climate change, MRO will do the following:

[17] 1. Observe seasonal cycles and daily variations of water, dust and carbon dioxide on Mars.

[18] 2. Characterize Mars' global atmospheric structure, atmospheric circulation, and surface changes to elucidate factors controlling the variable distributions of water and dust and to distinguish processes of eolian transport.

2.1.2. Aqueous Activity

[19] To search globally for sites showing evidence of aqueous and/or hydrothermal activity, the MRO will do the following:

[20] 1. Investigate local areas for compositional evidence of such environments, and in particular the presence of surface materials conducive to biological activity or having the potential for preserving biogenic materials.

[21] 2. Observe and quantify the detailed stratigraphy and geomorphology of key locales in order to identify formation processes of geologic features indicating the presence and persistence of liquid water.

[22] 3. Probe the horizontal and vertical structure of the uppermost surficial layer on Mars and its potential reservoirs of water and water ice.

2.1.3. Geosciences

[23] The MRO investigations will do the following:

[24] 1. Map and characterize in detail the stratigraphy, geomorphology, and composition of the Mars surface and subsurface at many globally distributed locales to understand better the nature and evolution of different Martian terrain types.

[25] 2. Characterize the Martian gravity field in greater detail to improve knowledge of the Martian crust and lithosphere and of atmospheric mass variation.

[26] The science objectives for MRO have been shaped by previous discoveries in surface morphology and composition, subsurface structure and ice content, and atmospheric circulation and state.

2.2. Mission Support Objectives

2.2.1. Orbiter Relay

[27] The value of telecommunications support by orbiting spacecraft through the relay of commands from Earth to landed spacecraft on Mars and through the downlink of data (mostly for science) from those landed craft on Mars back to Earth has been demonstrated many times, most recently by the continuing 2001 Mars Odyssey (ODY) support of the Mars Exploration Rovers. MRO will fly a UHF antenna and radio relay package, called Electra, to support the Phoenix lander in May–August 2008 and the Mars Science Laboratory (MSL) in late 2010. Although the nominal end of the MRO mission is December 2010, MRO carries enough fuel that it could continue to support relay through the one-Mars-year primary mission of MSL.

2.2.2. Site Characterization

[28] A different kind of mission of support is provided by the scientific instruments themselves, as they will provide information that will help identify sites for future landed exploration that have the highest potential for further scientific discovery and that are sufficiently free of hazards that future spacecraft can go there safely. In particular, an early priority for MRO will be observation of prime candidate landing sites for Phoenix and MSL.

2.3. Technology Demonstration Goals

[29] MRO is flying two technology demonstrations that can assist future scientific missions. These demonstrations are carried on a non-interference basis with the primary mission science, but can be used to enhance science from MRO, as well.

2.3.1. Optical Navigation Camera (ONC)

[30] By imaging the moons of Mars on approach, an optical navigation camera could provide precise navigation information that could guide a future lander to a highly accurate direct entry into the Martian atmosphere, thereby reducing the landed error ellipse. For example, this would enable a rover to land safely near an otherwise dangerous area of high scientific interest. On MRO, the ONC demonstrated this technique by imaging Mars during the last month of cruise prior to orbit insertion. Combined with other navigation information for MRO, these data also provide an improved ephemeris for the Martian moons.

2.3.2. Ka-Band Operations

[31] In the fall of 2001, it was decided to fly a Ka-band telecom package on MRO. Although Ka-band demonstrations had been conducted on previous deep-space missions, this package would be used to characterize the utility of the Ka-band frequencies for routine data return through the Earth's atmosphere over extended periods.

[32] Ka-band has the potential to return an equivalent volume of data with less power and more bandwidth than the nominal X-band packages now routinely flown. However, absorption by water vapor and liquid water is stronger at Ka-band than at X-band frequencies, so this experiment was designed to characterize loss in the Earth's atmosphere and to test strategies, including retransmission, that mitigate the loss when it does occur.

[33] Unfortunately, a failure in the Ka-band exciter chain during aerobraking and a possible impact on the nominal X-band telecom systems if the redundant paths were to be used have placed this operational demonstration of Ka-band on hold. During cruise the MRO Ka-band system set a new record for the rate of data return from deep space as part of in-flight testing. Detailed analysis of Ka-band performance during the MRO cruise is presented elsewhere [*Shambayati et al.*, 2006, 2007].

3. MRO Science Investigations

[34] In June 2001, in parallel with the release of the MRO AO, NASA formally selected a build-to-print version of the Mars Color Imager (MARCI) Wide-Angle Camera to fly on MRO. This instrument was one of two cameras [*Malin et al.*, 2001] lost on board the Mars Climate Orbiter (MCO). The second camera was a MARCI moderate-angle camera with a ground sampling distance (GSD) of 40 m/pixel. This camera was not reselected for MRO, because a similar camera (with an improved resolution of 18 m/pixel) was already included in the THEMIS instrument now flying on the 2001 Mars Odyssey orbiter.

[35] Instead, NASA formally invited Malin Space Science Systems, the builder of MARCI, to provide a new camera as a facility instrument to achieve wide-swath context imaging at still better resolution (<10 m/pixel). As indicated in the MRO AO, NASA directed the MARCI science team to operate both the MARCI (now meaning only the wide-angle camera) and this new Context Imager (CTX). In addition to operating CTX as a facility instrument, the MARCI team could plan additional observations as part of their own investigation. Dr. Michael Malin, of Malin Space Science Systems (MSSS), would thus continue as Principal Investigator (PI) for MARCI and was appointed as Team Leader (TL) for CTX.

[36] Also in June, NASA selected a new concept for the Pressure Modulator IR Radiometer (PMIRR) instrument, initially called the PMIRR Mariner Mark II. Two previously built PMIRR instruments had been launched to Mars and both were lost at orbit insertion, first on board the Mars Observer in 1992 and again with MCO in 1999 [*McCleese et al.*, 1992, 2007]. Making use of new advances in infrared detector arrays, the new instrument deleted the pressure modulators and the large passive radiator that were the core of the former instruments. The new instrument, reduced in mass and power from 40 kg, 45 W to 9 kg, <10 W, would still achieve essentially the same measurements goals as before. This redesigned instrument, later renamed the Mars Climate Sounder, was to be operated by the former PMIRR science team, with Dr. Daniel J. McCleese, of the Jet Propulsion Laboratory, California Institute of Technology, continuing as PI.

[37] In September 2001, ASI selected the Subsurface Sounding Shallow Radar (SHARAD) proposal written in response to their Announcement of Opportunity (AO-01-ASI-UPS-Mars Reconnaissance Orbiter 2005). Prof. Roberto Seu of the University of Rome was selected as Principal Investigator. (Since SHARAD is being provided as a facility instrument for flight on MRO, NASA formally recognizes Dr. Seu as Team Leader of the SHARAD investigation team.) In November 2001, NASA selected 3 U.S. Team Members for SHARAD in response to the NASA MRO AO, with Dr. Roger Phillips designated as Deputy Team Leader (DTL) to lead the U.S. contingent in support of Dr. Seu and his SHARAD science team.

Table 1. MRO Selected Science Investigations

Team	Type	PI/TL, Institution	Attributes
ACCEL	Upper Atmosphere Structure Investigation	Gerald Keating, TL George Washington Univ.	Profile upper atmosphere using spacecraft accelerometers during aerobraking
CRISM	Compact Imaging Imaging Spectrometer for Mars	Scott Murchie, PI Applied Physics Laboratory Johns Hopkins Univ.	Targeted Obs. & Multi-spectral Survey Emission Phase Functions Very High Data Rate
CTX	Context Imager	Michael Malin, TL Malin Space Science Systems	High Resolution Imaging Very High Data Rate
GRAVITY	Radio Science Investigation	Maria Zuber, TL Malin Space Science Systems	Data from DSN Tracking using s/c X & Ka Band Telecom Systems
HiRISE	High Resolution Imaging Science Experiment	Alfred McEwen, PI University of Arizona	Very High Resolution Imaging Very High Data Rate
MARCI	Mars Color Imager	Michael Malin, PI Malin Space Science Systems	Daily, Global Mapping Moderate Data Rate
MCS	Mars Climate Sounder	Daniel McCleese, PI Jet Propulsion Lab/Caltech	Atmospheric Limb Profiler Low Data Rate
SHARAD	Shallow Subsurface RADAR	Roberto Seu, TL/PI INFOCOM, University of Rome Roger Phillips, DTL	Radar Profiler Very High Data Rate

[38] Proposals submitted in response to the AO were reviewed for technical and scientific merit in the fall of 2001. On 9 November 2001 the NASA Associate Administrator for Space Science announced the final selections for MRO:

[39] 1. The High Resolution Imaging Experiment (HiRISE), with Prof. Alfred McEwen as PI from the University of Arizona and with Ball Aerospace (Boulder, CO) as a prime contractor for the telescopic imaging system.

[40] 2. The Compact Reconnaissance Imaging Spectrometer for Mars (CRISM), with Dr. Scott Murchie as PI from Johns Hopkins University's Applied Physics Lab.

[41] 3. Gravity Facility Science, with Prof. Maria Zuber as TL from the Massachusetts Institute of Technology and Goddard Space Flight Center.

[42] 4. Upper Atmospheric Structure (also Accelerometer), with Dr. Gerald M. Keating as TL from George Washington University.

[43] Table 1 summarizes the eight scientific investigations selected for the Mars Reconnaissance Orbiter mission.

[44] In the fall of 2002 NASA confirmed the MRO Project's strategy for development of the launch vehicle, the spacecraft, the eight science investigations with their six payload instruments, and key elements of the mission design, including operation of the instruments for one Mars year in a redesigned near-circular primary science orbit (see section 4.1).

[45] This confirmation also included specification of individual instrument capabilities, particularly those outlined in the MRO AO to ensure a major advance in the capabilities of near-IR spectrometric imaging and in visual imaging. In all cases, the realized capabilities (shown in Table 2) meet or exceed the specific requirements stated in the AO.

[46] The following gives a brief introduction to the MRO science investigations. More detailed descriptions are given in the references, many of which are in this special section.

3.1. Mars Color Imager (MARCI)

[47] MARCI consists of two framing cameras, the first with two spectral bands in the ultraviolet and the second with five in the visible. This instrument will produce daily global maps of weather on Mars and, in particular, will routinely track ozone as a proxy for water vapor. This instrument was designed to continue the daily global survey of weather on Mars that had been started by the Mars Global Surveyor's (MGS) two-color Mars Orbiter Wide-Angle Camera (MOC).

[48] A key difficulty for MARCI and MCS was that they were originally designed for an orbiter (MCO) that was constantly nadir pointed at Mars. Thus accommodation on

Table 2. MRO Science Instrument Capabilities

Instrument	Capabilities (Ref. to 300 km)	
CRISM	*Multi-spectral Survey* ~70 channels ~200 m/pixel bin	*Hyperspectral Imaging* 18 m/pixel 10.8 km swath 6.5 nm spectral resoln 0.4–3.92 μm
CTX	High Resolution Imaging Panchromatic (minus blue) Stereo by Revisit	6 m/pixel 30 km swath SNR > 20
HiRISE	Very High Resoln. Imaging 1.2 km swath (NIR & BG) Stereo by Revisit	0.3 m/pixel 6 km swath (red) SNR > 150
MARCI	Daily Global Monitoring 180° FOV	7 Bands 0.28–0.8 μm 5 VIS: 1–7 km/bin 2 UV: 10–30 km/bin
MCS	Daily Global Profiling Broadband solar 8 thermal IR arrays	Limb Sounding 0–80 km. ~5 km vertical resoln
SHARAD	Radar Profiler 1 × 6 km footprint Profile to ~0.5 km depth	15–25 MHz band SAR processing down-track ~10 m vertical resoln

MRO for which off-nadir pointing is a major and frequent activity required hardware or operational changes.

[49] To accommodate off-nadir rolls, the field-of-view of MARCI was expanded from 140-deg, which normally would cover the planet's atmosphere and surface from limb-to-limb, to 180-deg. The instrument also had to be modified to work with the low-voltage differential signaling (LVDS) serial data interface used by MRO, but not by MCO. These were the only major changes to this otherwise build-to-print instrument.

[50] The daily global survey of the Mars atmosphere by the MRO MARCI will continue and augment the MOC observations, providing a decade-long climate record. There was a brief overlap of observations for a few days before solar conjunction. However, the unexpected loss of contact with MGS shortly after solar conjunction precludes further observations in parallel by MRO and MGS.

[51] MARCI global maps will also aid the entry and descent and surface operation phases of lander missions (Phoenix and potentially the Mars Science Laboratory) by characterizing atmospheric conditions, especially dust storm activity. Its data will also alert the MRO instruments to atmospheric seeing conditions.

[52] MARCI goes beyond MOC in that its ultraviolet channels will be used to routinely monitor ozone. In the Mars atmosphere the spatial distribution of ozone is closely anti-correlated with that of water vapor due to photochemical processes. (Photo-dissociation of water vapor produces trace gases containing hydroxyl that catalytically destroys ozone molecules.)

[53] Thus MARCI will expand upon the present climatological records of atmospheric variation, atmospheric processes, and their inter-annual variability. MARCI will also detect changes in surface properties as dust is redistributed locally, regionally and occasionally globally around the planet [see *Malin et al.*, 2007].

3.2. Mars Climate Sounder (MCS)

[54] MCS represents a continued thrust to quantify atmospheric structure and circulation. As was the case for PMIRR [*McCleese et al.*, 1992], MCS is designed to provide atmospheric profiles of temperature, dust and water vapor distribution using remote sensing measurements at thermal infrared wavelengths. The vertical profiles of temperature and dust and the column water (vapor and ice) abundances derived from these data will continue the 3–4 Mars year climatology record produced by the Mars Global Surveyor (MGS) Thermal Emission Spectrometer (TES) instrument.

[55] There will be a gap in this temperature/dust/water vapor climatology before MCS begins observations in the fall of 2006, due to an end-of-life degradation of the TES wavelength calibration lamp (which has lasted well past its design lifetime). Measurements using a TES bolometric channel and a narrowband channel on THEMIS, together with spectral measurements by the Planetary Fourier Spectrometer (PFS) on Mars Express, can help bridge the gap between TES and MCS measurements. Overlapping measurements may reveal instrument biases that would otherwise complicate analysis of long-term trends in the Martian atmosphere. Past data already show that the seasonal cycles of the Mars atmosphere vary from year to year. Further measurements are required to isolate the underlying mechanisms of seasonal changes and their interannual variability.

[56] MCS goes beyond the previously mentioned atmospheric experiments (and the MRO CRISM) in that it observes the atmosphere more frequently. It uses its own scanning mechanisms to view sequentially the atmosphere beneath the spacecraft and above the limb of the planet to provide better vertical resolution (typically 5 km for MCS versus 10 km or more by previous instruments). A key measurement will be water vapor, from <5 to 35 km altitude. Measurements at lower altitudes (<2–5 km) will intersect the surface, and water there must be estimated by combining limb and nadir views. An additional MCS objective is the radiative balance of the seasonal polar caps, as measured through a combination of thermal IR channels and a broadband solar channel. To provide as quantitative a measure of reflectance by the seasonal frost as possible, MCS employs an external solar calibration target and uses a two-axis scan mechanism to get angular coverage of surface reflectance.

[57] MCS coverage is affected by off-nadir targeted observations because spacecraft rolls rotate the limb view of the detector arrays, thereby mixing emission from different altitudes in an undesirable way. For large rolls (>9°) the array field of view can be lifted off the planet entirely. MCS operations are also interrupted during very-high-resolution imaging, both nadir and off-nadir, when its field of view is "frozen" looking at the limb. By suspending scanning for several minutes (during which time the spacecraft nadir point moves ~45° of latitude), this MCS "freeze-mode" prevents the jitter from its articulating motors from smearing the highest-resolution images. A series of guidelines ("the MCS rules") are used when planning targeted images to lessen the impact on MCS; exceptions to the guidelines are discussed in the Target Acquisition Group (TAG) meeting as part of the planning process (see section 6.1). Such guidelines are practical since the MRO orbit repeat cycle provides many opportunities to view a given place in a relatively short period of time (section 4.1). These interruptions in the MCS coverage are significant, but presently judged to be workable, preserving the ability to build on and to expand the 7-year climate record [see *McCleese et al.*, 2007].

3.3. Compact Reconnaissance Imaging Spectrometer for Mars (CRISM)

[58] Given the many morphologic features on the Martian surface that indicate that water once flowed there, it has been surprisingly difficult to find compositional evidence that water was ever persistent on the surface. The indication from TES data that Sinus Meridiani, one of three areas bearing the plausible signature of an aqueous mineral (hematite), was so unique that one of the two Mars Exploration Rovers (MER) was directed there, where it confirmed that this was a place where water (and groundwater) had once flowed. However, many questions remain about the timing, extent and duration of water activity on and just beneath the Martian surface.

[59] Experience with Mars indicates that progress on these issues can be made by exploiting remote sensing measurements at complementary wavelengths or by observ-

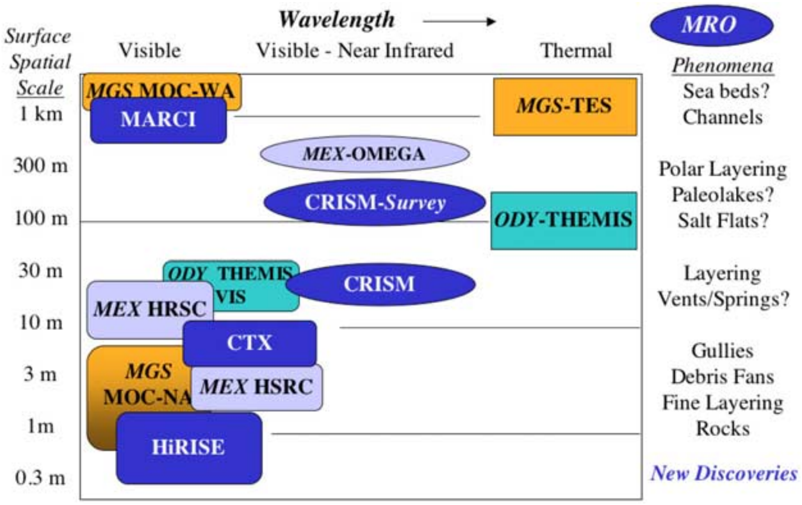

Figure 1. Spatial resolutions for imaging instruments now flying on Mars Global Surveyor (MGS), Mars Odyssey (ODY), and Mars Express (MEX) are compared schematically with MRO capabilities (dark blue). Resolution increases in the chart from top to bottom, with instruments separated by column into visible, near-IR, and thermal IR wavelength regions.

ing at higher spatial resolutions. Given the thermal IR measurements already in hand (from TES and now at 100-m resolution by THEMIS), it seemed prudent to both NASA and the European Space Agency (ESA) that visible and near-infrared measurements at the right spatial and spectral resolutions could reveal whether aqueous deposits were there on the surface (at least at depths of a few centimeters).

[60] The OMEGA instrument on the ESA Mars Express orbiter has been observing Mars for more than a Mars year from a highly elliptical orbit. Even with spatial resolutions of several hundred to five thousand meters, this visible-near infrared imaging spectrometer has shown that numerous areas of Mars have a diverse composition, including hydrated sulfates, phyllosilicates, and pyroxenes [*Bibring et al.*, 2005]. Measurements by both OMEGA and by the MER instruments have produced major advances in our understanding of Mars surface materials, but the synergy of these measurements is just beginning. A major question is what features in surface composition will be revealed when observed at even higher spatial resolution.

[61] CRISM on MRO brings new capabilities to the field, both in the instrument itself and in the MRO mission capabilities. Observations from a near-circular, low-altitude orbit will boost resolution and simplify mapping the data into regional and global mosaics. Data return capacity expands the coverage at moderate to high resolution.

[62] In its nadir-viewing survey mode, CRISM on MRO can cover most of the planet at resolutions $\leq$200 m/pixel in more than 70 bands chosen out of 512 bands spanning wavelengths from 0.4 to 3.96 microns.

[63] For the most promising regions CRISM can use its articulating instrument to slow down the apparent ground imaging speed and thereby achieve full spectral resolution over a swath 11 km wide at a spatial resolution just better than 20 m/pixel. Furthermore, by viewing the targeted locale through a range of atmospheric emission angles CRISM provides the data needed to remove atmospheric features from the sunlight reflected by both the surface and the atmosphere, thereby isolating the surface compositional signature. Independently, these measurements also provide key data about atmospheric thermal structure, dust loading and water vapor column abundance. They are taken on a latitude-longitude grid at monthly intervals.

[64] There is much to learn about the climate history of Mars from this compositional data, especially in combination with geomorphologic data. CRISM provides a key link via its well-calibrated and high-precision instrument, with its cooled detectors and high sensitivity [see *Murchie et al.*, 2007].

3.4. High Resolution Imaging Science Experiment (HiRISE)

[65] HiRISE is designed to return images of Mars with unprecedented spatial resolution and quality. From 300 km altitude the pixel dimension on the surface is just 30 cm and yet its central ten charge-coupled devices (CCDs) combine to span nearly 6 km in a single swath. Using two extra pairs of CCDs, HiRISE also can provide 3-color images across the central stripe, 1.2 km wide.

[66] This increase in resolution is shown schematically in Figure 1. Note that currently the MGS MOC narrow angle camera provides the best image resolution. MOC has a best pixel scale of 1.5 m in a 3 km swath from the MGS orbital altitude ($\sim$400 km). Finer sampling in the downtrack direction has been achieved via a clever maneuver in which the MGS spacecraft pitches over to slow the ground track speed (much as CRISM does by itself on MRO). This enables MOC to decrease its downtrack sampling to 50 cm/pixel, although the cross-track dimension remains the same.

[67] Thus HiRISE improves the current best resolution from Mars orbit by a factor of 2 for down-track viewing and a factor of 5 for the best of normal MOC observations, as well as all cross-track sampling. HiRISE combines this capability with exceptionally high signal-to-noise in all cases thanks to its time-delayed integration capability.

[68] Stereo images can also be acquired, though it requires targeting the same site on different orbits (unlike the High-Resolution Stereo Camera (HRSC) on Mars Express). Together, these HiRISE capabilities promise to provide incredible detail and insight into Mars history as represented by the surface morphology and stratigraphy at the smallest scales yet resolved without landing [see *McEwen et al.*, 2007].

[69] Exploiting these capabilities to their fullest requires the MRO to return high volumes of data, provide high stability while imaging and point accurately especially for stereo. Even so, the increased resolution will still mean that the very highest resolution images will cover a few tenths of 1% of the planet. By binning pixels, 1% of the planet can be covered by HiRISE. By comparison, in nearly a decade of observation MOC has covered about 5% of Mars, but less than 0.5% at resolutions better than 3 m/pixel (M. Malin, private communication, 2005). A particular challenge for analyzing HiRISE images is their size: a full HiRISE image, read out from all 14 CCDs, is 28 Gbits of information! This poses a severe challenge for distribution and viewing of these images, and the team has adopted the JEPAG2000 standard to address this issue [see *McEwen et al.*, 2007].

3.5. Context Imager (CTX)

[70] The provision of a context camera as a facility instrument on board MRO resolved a debate in the science community about whether the acquisition of moderate-resolution (<10 m/pixel) image data over a large fraction of Mars was in fact a greater need than very high resolution data over a necessarily more limited area.

[71] On any other spacecraft, CTX with its 6-m/pixel resolution from 300 km would be the high-resolution imager. While this resolution is a factor of four lower than the best achievable by MOC (in nadir mode), it is very comparable to the resolution achieved on average by MOC, since 80% of the MOC images and areal coverage have been taken at a resolution $\geq$4.5 m/pixel, 40% at resolutions $\geq$6-m/pixel. A typical CTX image will also be 10 times wider and 5 times longer than its MOC counterpart [see *Malin et al.*, 2007]. With its 30 km swath and 13% allocation of the MRO data return, CTX can cover 15–20% of Mars at its best resolution during the PSP. This coverage is comparable to that returned over a longer period by the Odyssey THEMIS-VIS camera at 18 m/pixel.

[72] CTX and HiRISE thus respectively meet the needs for both expanded coverage at resolutions nearly as good as the current best and the ability to zoom in on targeted areas at very high spatial resolution. Their large swath widths, together with their ability to bin pixels and the requirement that both view selected targets simultaneously, ensures that the MRO images can be interpreted relative to each other and to other, lower-resolution images (e.g., HRSC and Viking).

[73] The advantages of CTX are its potential for extended coverage with excellent spatial resolution and its team's vast experience with MOC. In concert with other MRO instruments and on its own, CTX seems sure to reveal new relationships between surface features and thereby provide new insights into local, regional and global development of the Martian surface and climate [see *Malin et al.*, 2007].

3.6. Shallow Radar (SHARAD)

[74] Until recently, little was known about the properties of the subsurface of Mars beyond a meter's depth. A few Earth-based and orbital bistatic radar experiments had shown discoveries, such as the "stealth region" with its low signal return [*Muhleman et al.*, 1991]. Measurements by the Gamma Ray suite of instruments on Mars Odyssey indicated a significant amount of ice in the top meter of ground over most areas at middle to high latitudes [*Boynton et al.*, 2002], but it is not known how deep such ice extends into the surface.

[75] The multifrequency MARSIS radar pulses are at relatively low frequencies (<5 MHz), so designed to achieve deep penetration into a subsurface whose dielectric properties at depth were essentially unknown. In anticipation of a successful outcome of the MARSIS experiment (meaning that the subsurface would not be too attenuating at these wavelengths), the SHARAD instrument was designed with a single, higher-frequency band pass (of 10 MHz) with a central wavelength at 20 MHz. This higher frequency would give significantly higher vertical resolution (estimated at around 10 m), although it would also be more attenuated. Early analysis of the MARSIS data suggests that SHARAD should be able to penetrate up to half-a-kilometer deep. MARSIS detections of buried craters, some possibly containing ice, on the northern plains and of layers in the north polar ice and in the south polar layered terrain [*Picardi et al.*, 2005] highlight the kinds of features that SHARAD will better resolve.

[76] A key challenge in the analysis of radar data is to account properly for surface clutter and to separate the many possible contributors in the subsurface. This has been successfully done with the MARSIS data [*Picardi et al.*, 2005]. Coordinated observations can help address potential ambiguities through comparison with other MRO data. The confirmation of layers detected beneath smooth plains and exposed in canyon or crater walls is one such example. Other approaches use the crossing of radar tracks, which will occur most frequently at higher latitudes.

[77] By probing several hundred meters into the surface, SHARAD will test whether the ice detected near the surface by Odyssey is merely in equilibrium with the atmosphere today or literally is the top of a deeper cryosphere or permafrost regime. Better resolution of the radar returns in polar ice and other layered material will further test models of climate change associated with changes in obliquity or orbital eccentricity and phasing. SHARAD will provide a third dimension to the study of the Martian regolith [see *Seu et al.*, 2007].

3.7. Gravity Science

[78] MRO will be at a lower altitude (see Figure 2) in its primary science phase than either MGS or ODY were. This means that the spacecraft is more sensitive to the shorter wavelength features of the Martian gravity field. Mapping these components and understanding their implications for crustal structure and evolution is a key goal for the Gravity Science team, one of two teams chosen to use the spacecraft itself as the measurement device. Doppler data acquired by tracking the spacecraft on a daily basis provides the needed data. Furthermore, the investigation on MRO can compare results from tracking using X-band

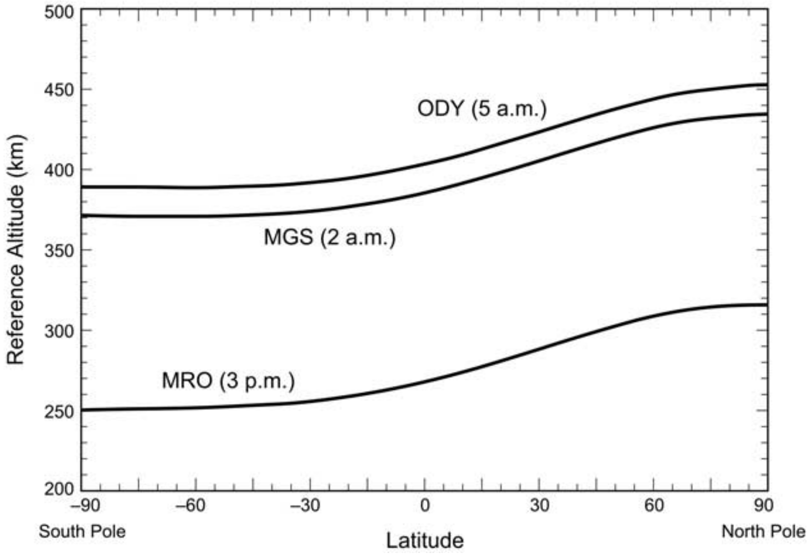

Figure 2. Orbital altitude as a function of latitude for MRO, MGS, and ODY. The variation from south to north is due to asymmetries in the Martian gravity field. The periapsis altitude of the highly elliptical Mars Express orbit traces a path similar to the MRO orbit at varying local times.

data with that from Ka-band data, assuming recovery of that technology demonstration.

[79] A second analysis planned by the gravity science team is less conventional and involves analyzing the time-dependent component of the Martian gravity field [*Smith et al.*, 2001]. This time variation is due to the substantial mass exchange that occurs as the southern and northern seasonal carbon-dioxide caps grow and shrink in their respective fall/winter and spring/summer seasons. Mass is exchanged between the global atmosphere and the polar surface as CO_2 freezes at, or falls onto, the surface in the annual polar night, and then sublimes back into the atmosphere when sunlight returns. A key goal is to further characterize this mass exchange (its amount and distribution) over the Martian year by analysis of MRO tracking data [see *Zuber et al.*, 2007].

3.8. Upper Atmospheric Structure From Accelerometer Data

[80] On each of nearly 450 aerobraking orbits, measurement of the deacceleration of the spacecraft as it passed through the atmosphere provided a time history of density along the orbit path that can be analyzed in terms of the vertical and horizontal density distribution and to a lesser extent with time of day and season. These atmospheric structure measurements provide key insights into the upper atmosphere (>100 km) and thus into processes that may ultimately result in the loss of atmospheric gases, especially water vapor, to space. They also provided an immediate measure of whether the spacecraft was, and would continue to be, at the right altitudes for aerobraking. For this reason the analysis of the MRO accelerometer data had a dual purpose: First, to support aerobraking operations of MRO on a timely basis and second, to provide a data set useful for science.

[81] Similar measurements made during aerobraking of the MGS and ODY spacecraft have produced a tantalizing, but incomplete picture of the upper atmosphere. Aerobraking measurements by MRO will help fill in that picture, while also providing important information for future aerobraking missions. Improvements in the electronic readout of the MRO accelerometers provided sensitivity to densities over a greater height range (often as high as 200 km on the inbound leg) than Odyssey and comparable to MGS.

[82] During MRO aerobraking its periapsis moved from high southern latitudes toward and past the South Pole during (southern) fall, a time when the wintertime polar vortex was well formed in the lower atmosphere. As aerobraking came to an end in August 2006, periapsis moved back to equatorial latitudes at different local times but still on the night side. MGS also recorded data from a south pole passage during winter, but that was at a different local time and different solar cycle (both were close to solar cycle minimum), at a slightly different season, and, most importantly, in a different Mars year.

[83] Comparisons of data from the various missions will help characterize key cycles of variation in space and time. Such data are critical to the validation of upper atmospheric circulation models used to understand high-altitude variability and transport processes, as well as to validate engineering models used to plan future missions. Such a model was used to assist planning of the MRO aerobraking and science phases [see *Bougher et al.*, 2006].

4. Mission and Spacecraft Design

[84] The science objectives for the MRO mission resulted in the selection of several high-capability instruments with sometimes competing operational modes (e.g., nadir versus off-nadir) and nearly all designed to improve substantially the resolution of individual scientific observations while maintaining or increasing coverage. This posed several challenges for the mission design, spacecraft design and payload accommodation.

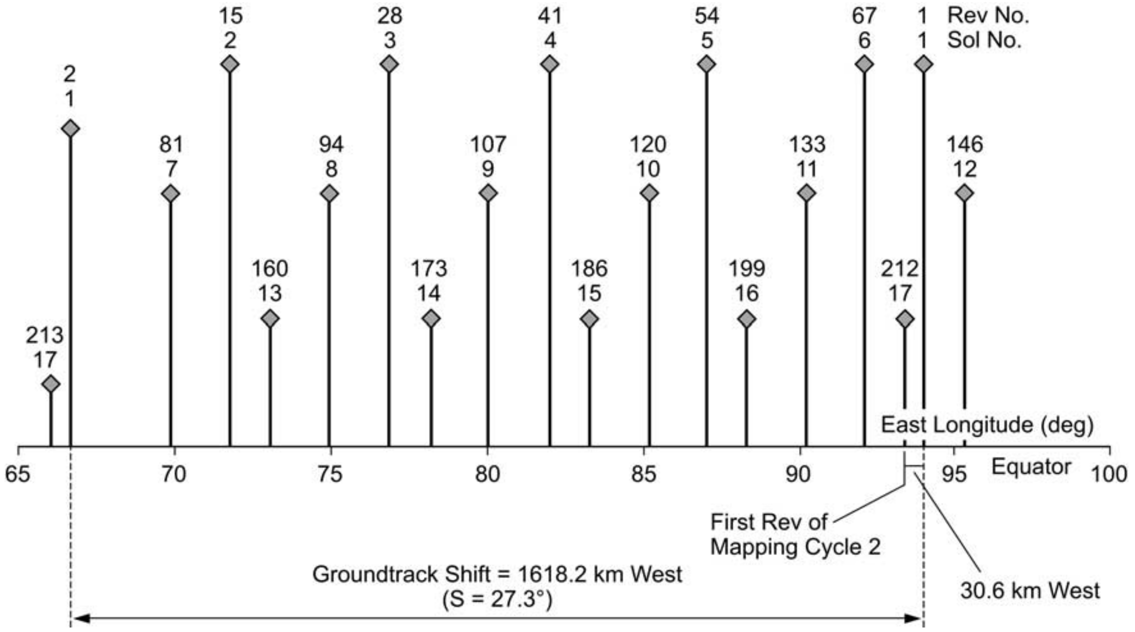

Figure 3. The locations of subsequent ground track crossings are shown for a segment of longitude (in degrees) spanned by two adjacent MRO orbits. This pattern is replicated in each of the ~13 segments that encircle the globe in a single Martian day (sol). The three tiers of lines are labeled with the orbit and sol number for the three ~5-day sweeps that individually and collectively divide the daily interval between two sequential ground tracks into roughly equal segments, nearly repeating over a 17-day cycle.

4.1. Primary Science Orbit (PSO)

[85] After aerobraking, MRO executed two propulsive maneuvers that inserted the orbiter into a Primary Science Orbit (PSO) from which its science instruments will observe Mars for at least one Martian year. The PSO is a low-altitude, near-circular (250 × 315 km), near-polar (inclination of 92.65°) orbit, with an ascending node on the dayside of the planet fixed near 3 p.m. local mean solar time. This orbit is ''frozen'' so that its periapsis is fixed over the South Pole and the spacecraft crosses each latitude circle at essentially the same altitude on every orbit; the choice of a nearly polar orbit ensures that nearly all latitudes will be crossed.

[86] The altitude and near-circularity of the orbit are a compromise, in that a lower orbital altitude would enhance spatial resolution for the imaging systems; however, the greater atmospheric drag at lower altitudes would require frequent orbit trim maneuvers. In addition to this being a lien on the fuel required for normal operations, the frequent spacecraft trims would mean that prediction errors of spacecraft position would rapidly grow and limit the ability to target the instruments at specific locales. Thus, although the orbit is lower than that of MGS and ODY (see Figure 2), it does not go as low as the initial design of a 200 × 400 km orbit.

[87] Such an elliptical orbit would permit higher-resolution targeting near periapsis. To see all parts of the planet at the best resolution would then require the periapsis to rotate around the planet (much like the orbit for Mars Express). However, unlike the frozen orbits, this periapsis movement would mean that different over-flights of areas at the same latitudes would be at significantly different altitudes, unless one waited (typically one or more months) for periapsis to rotate around once again to that latitude. Also, during half of this time periapsis would be on the night side, precluding high-resolution imaging near periapsis during those periods.

[88] The frozen, near-circular PSO facilitates building daily global maps, making regional observational mosaics, and rapid acquisition of both images of a stereo pair at consistent resolutions. Furthermore, the choice of altitude was carefully chosen to yield a ground track repeat cycle such that nearly all locations on the planet can be viewed within 17 days by pointing the spacecraft off-nadir by up to 20° (larger rolls are required near the equator and very near the poles). This primary repeat cycle has a shorter ~5 day repeat cycle, such that ground track longitudes are roughly equally spaced in 1, ~5, and ~17-day periods (see Figure 3).

[89] The fastest cycle, of course, is due to the orbit period of 112 minutes (yielding ~13 orbits a Martian day or sol); this permits the systematic global daily sampling needed by MARCI and MCS to monitor the Martian atmosphere. While the faster repeat cycles aid atmospheric monitoring, the 17-day cycle ensures multiple opportunities to view any given point well within a Martian season. This facilitates compromise when choosing targets for any given period and also ensures that the two images taken for a stereo pair are not too widely separated in time, thereby minimizing surface and atmospheric changes between the two images.

[90] The final compromise chosen for the PSO was the choice of 3 p.m. (presently 3:03 p.m.) as its local mean solar time. Earlier times produce less surface contrast for the visible imagers (CTX and HiRISE); later times reduce the signal for CRISM which observes reflected sunlight and for MARCI as the eastward limb is closer to the terminator. Later times also impact on-planet views by MCS in that the

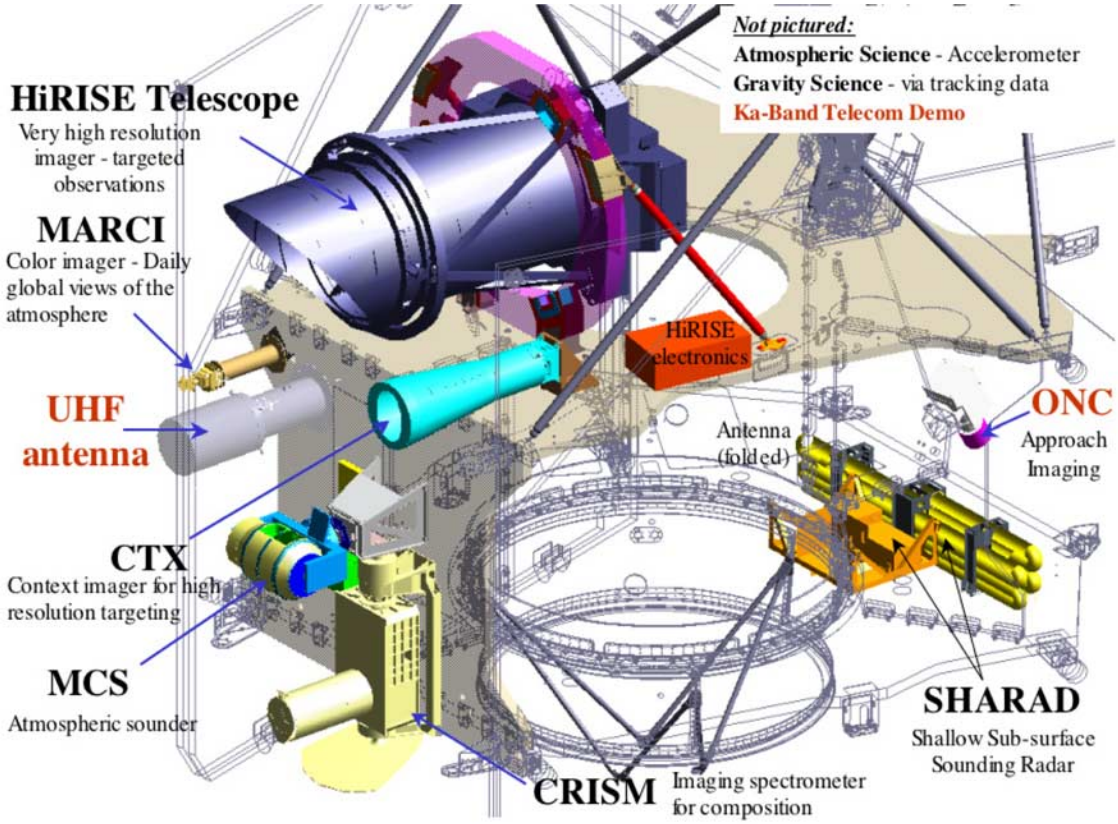

Figure 4. MRO science instruments (black captions) and engineering components (red captions) shown as deployed mainly on the spacecraft nadir (Mars-facing) panel and middle deck. ONC is mounted on the far-side of the spacecraft, where it viewed Mars on approach. SHARAD, with its antenna (shown in the folded position before deployment in mid-September) is mounted on the aft deck of the orbiter, near the main engine cluster. (Note added in proof: MARCI was relocated along the deck edge below the UHF antenna; see Figures 5 and 8.)

air-ground temperature contrast is small late in the afternoon, complicating atmospheric retrievals.

4.2. Spacecraft Design

[91] The MRO mission posed many challenges to the spacecraft development team. The orbiter would have to accommodate several instruments, including the largest camera (HiRISE) to be flown into deep space. Even the smaller instruments (MARCI and MCS) had demanding fields of view. Figures 4 and 5 show the final payload accommodation, with the instrument axes pointing in the nominal nadir direction, except for SHARAD, which was mounted on the opposite side at the aft end of the orbiter to accommodate its 10-m antenna (shown folded in the figures). Mass, power and volume specifications for the science payload, including ONC, are given in Table 3.

[92] While daunting in their own right, these accommodation issues are typical for most missions. The implications of very-high-resolution observations were the real science drivers for MRO. These included the need (1) to return huge volumes of data from deep space (i.e., Mars); (2) to target accurately hundreds of local areas on Mars despite operating at lower altitudes; and (3) to minimize orbiter jitter when operating the imagers, especially HiRISE, with its time delayed integration approach to very high resolution imaging.

[93] Targeting requires rolling the spacecraft up to 30° off-nadir in either direction, waiting (several minutes) for the spacecraft to settle, commanding the instruments to observe, and then rolling back to nadir orientation. The spacecraft also does a continuous yaw (twist) that takes out the ground motion due to the planet's rotation. Spacecraft rolls affect power generation because the solar arrays are not at their best position relative to the Sun for 12–20 minutes and it complicates data return, as the spacecraft strives to keep its high-gain antenna (HGA) pointed to Earth. (Because the range of motion of its articulating gimbals is limited, the HGA must “rewind” once an orbit, moving back to the starting position for tracking the Earth. This is done during Earth occultation, which often coincides with eclipse, when the imagers are not used.) The MRO can support up to four ±30° rolls on a given orbit; typically, 1–2 smaller rolls are typically planned in order to not produce too many gaps in the coverage of the mapping instruments (principally MCS).

[94] To meet the need to target hundreds of locales over the 2-year science mission at the relatively low altitude of the PSO, the spacecraft was designed to use an onboard Integrated Targeting List (ITL) in combination with the latest available ephemeris uplinked to the spacecraft in order to increase the probability that the desired target would actually be observed.

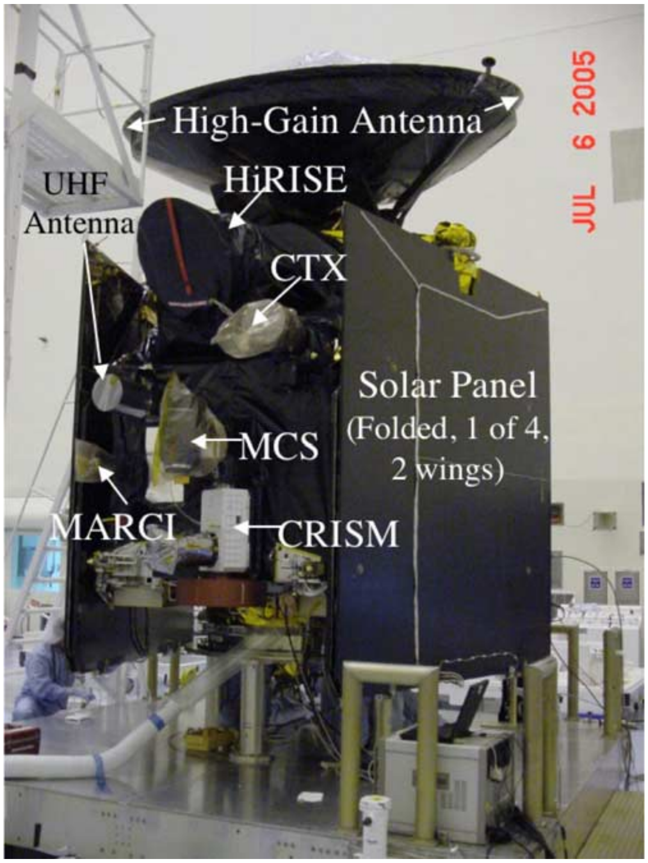

Figure 5. MRO at the Kennedy Space Center facility prior to integration with the ATLAS V launch vehicle. The 3-m HGA at the top, the folded solar arrays, the protective thermal blankets, and the instruments on the nadir deck (with their protective covers and purge bags) are visible.

[95] To meet the jitter constraints, the gimbals and motors that articulated the solar arrays and high gain antenna were designed (with increases in size and mass) to minimize jitter while supporting the constant articulation needed to power the spacecraft and payload in a mid-afternoon sun-fixed orbit and to communicate with the DSN stations for most, and occasionally all, of each day during a two-year science phase. During the very highest resolution observing, the solar arrays (along with the MCS scanning) can be paused, if required. In-flight performance has demonstrated that the HGA and solar arrays can continue to track without adverse jitter effects.

[96] To meet the need for a major increase in data return rate, the spacecraft was equipped with a 3-meter high gain antenna (Figure 5) and two powerful 100 W X-band traveling wave tube amplifiers (TWTAs). A solid-state recorder (SSR), with a capacity of 160 Gbits, accepts raw data directly from the instruments and framed data for downlink. The SSR also provides a hardware compressor that can be used on HiRISE data, reducing the volume by an additional factor of ~1.7. The Ka-band system, with its 35 W TWTA, was also incorporated. Two solar array wings, totaling 20 square meters in area (Figure 5) and generating 600 W of power even at Mars aphelion and end of mission, charge two 50 Amp-hr battery systems which provide the electricity needed to operate these and other spacecraft subsystems, together with the payload, simultaneously.

[97] The resulting spacecraft is significantly larger than the Mars Global Surveyor and Mars Odyssey spacecraft, previously built by Lockheed-Martin for the NASA Mars Exploration Program. The spacecraft has an approximate height of ~7 m when the HGA is stowed (Figure 5). Its width from the tip of one solar array to the other, when both are extended, is ~14 m. At launch, the spacecraft weighed 2180 kg including 1199 kg of fuel for its 20 thrusters, including the six main thrusters. The spacecraft also has a more open structure, which provided some additional challenge to reducing electromagnetic interference (EMI), but also proved very efficient when integrating the major spacecraft power, memory and computer boxes.

[98] In addition to the payload requirements, the spacecraft was required to be able to operate in the PSO until December 2010 and it was to carry a propellant load that would enable 10 years of mission life after launch (until 2015).

[99] These capabilities were developed, implemented and tested during a design, development, and integration phase from 2002 to 2005.

4.3. Data Return

[100] MRO will support high-rate downlink transmissions of an X-band carrier modulated with engineering, navigation and science data through 2 eight-hour passes each day to 34 m antennas in the Deep Space Network (DSN), with the capability to downlink to 70 m antennas at even higher rates. Presently, three X-band passes per week to the 70-m antennas are added when MRO is at greatest range from Earth, at the beginning and the end of the PSP.

[101] The present capability for data return by MRO is shown in Figure 6 as a function of time during the primary science phase, starting in November 2006 and ending in December 2008. Note that the added 70-m coverage occurs at the beginning and end of this period, when MRO is at greatest range from Earth and the data rate is smallest.

[102] These data are returned to a raw science data server at JPL and made available for transfer to the data processing centers at the individual science investigation home institutions. At present, the MRO project, including its science teams, is funded to process 26 Tb of data into experiment data records (EDR) and standard reduced data products (RDR). The project baseline is for acquisition of 34 Tb of data.

[103] This baseline of 34 Tb provides a margin of nearly 50% above the 26 Tb return required for full mission success. Given the performance of the telecom system to date, MRO is on track to return up to twice the amount

Table 3. MRO Payload Specifications

Instrument	Mass, kg	Power, W (Orbital Avg.)
CRISM	33.1	46
CTX	3.5	6
HiRISE	65.1	60
MARCI	1.0	3
MCS	9.0	2
SHARAD	16.6	6
ONC	2.9	16 (cruise)
Payload	132	189 (with reserve)

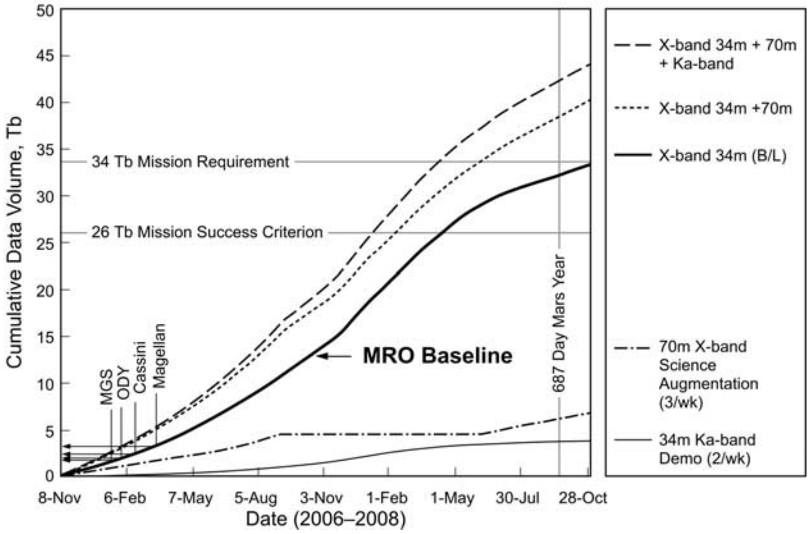

Figure 6. The cumulative volume of data that MRO is expected to return during its primary science phase is shown using the twice daily X-band passes to 34-m DSN antennas. The effect of adding baselined 70-m passes and of the possible contribution via Ka-band passes is also shown. The arrows indicate the volumes of data returned by other deep space missions during their prime science phases, as a way of illustrating the challenge presented by MRO.

(50 Tb) required for full mission success. The science teams are not funded to generate standard products for data acquired beyond the 26-Tb goal, but will process all data through EDRs with further processing done for the additional data on a best-efforts basis. In most cases additional data will be used to increase individual image size, reduce the degree of compression, minimize binning, or add spectral channels to already planned coverage, rather than to choose more targets. This reduces the burden that additional data taking would otherwise impose on the science planning process.

[104] Data allocation by instrument team for the acquisition of 26 Tb (over the two-year PSP) is indicated in Table 4. Engineering, SPICE, MCS, tracking (for gravity science) and accelerometer data are not counted against these allocations because of their small volumes.

5. Mission Status: Progress and Expectations

[105] The MRO flight mission is divided into several main phases: Launch, Cruise, Aerobraking, Primary Science, and Relay. Cruise was further divided into Early Cruise, Cruise, Mars Approach and Mars Orbit Insertion. The aerobraking phase also included a Transition subphase which bridged between the end of aerobraking maneuvers and the start of the Primary Science Phase (PSP). Solar conjunction occurred during this subphase in October 2006 and will come again at the end of the PSP in December 2008. Although relay is an identified phase, relay support for the Phoenix mission, launched in 2007, occurs during the latter third of the Primary Science Phase. The timelines of mission phase activity are given in Figure 7.

5.1. Early Phases

5.1.1. Launch and Cruise

[106] On 12 August 2005, two days into a 23-day launch period, the Mars Reconnaissance Orbiter was launched aboard an ATLAS V-401 provided by Lockheed Martin through its International Launch Services. The ATLAS V-401 had a four (4)-meter diameter fairing, no (0) solid boosters and a single (1) engine Centaur upper stage (thus 401). This configuration was certified for NASA use in March 2005, and the MRO was the first government payload to be launched on the ATLAS V. Launch was flawless, with the MRO deploying its solar arrays shortly after separation from the Centaur second stage, followed shortly by deployment of the high-gain antenna, all without incident, high over the Pacific Ocean.

[107] During the seven-month cruise to Mars, the spacecraft executed 2 trajectory course maneuvers to adjust its flight. The first of these used the 6 100-N main thrusters as a check of the propulsion system required to insert MRO into an orbit around Mars. The second course correction was so precisely executed and the spacecraft in its cruise configuration (solar arrays and HGA in a fixed attitude, pointed at Earth) so balanced that the remaining two trajectory course maneuvers were canceled. Two contingency maneuver opportunities on the close approach to Mars were also not needed, and the spacecraft entered Mars orbit without incident on 10 March 2006.

[108] During cruise the orbiter performed a series of check-outs of spacecraft subsystems and of the payload. These included several functional checkouts and calibra-

Table 4. MRO Data Volume Allocations

Instrument	Allocation	% × 26 Tbits
CRISM	30%	7.8
CTX	13%	3.5
HiRISE	35%	9.1
MARCI	7%	1.6
SHARAD	15%	4.0

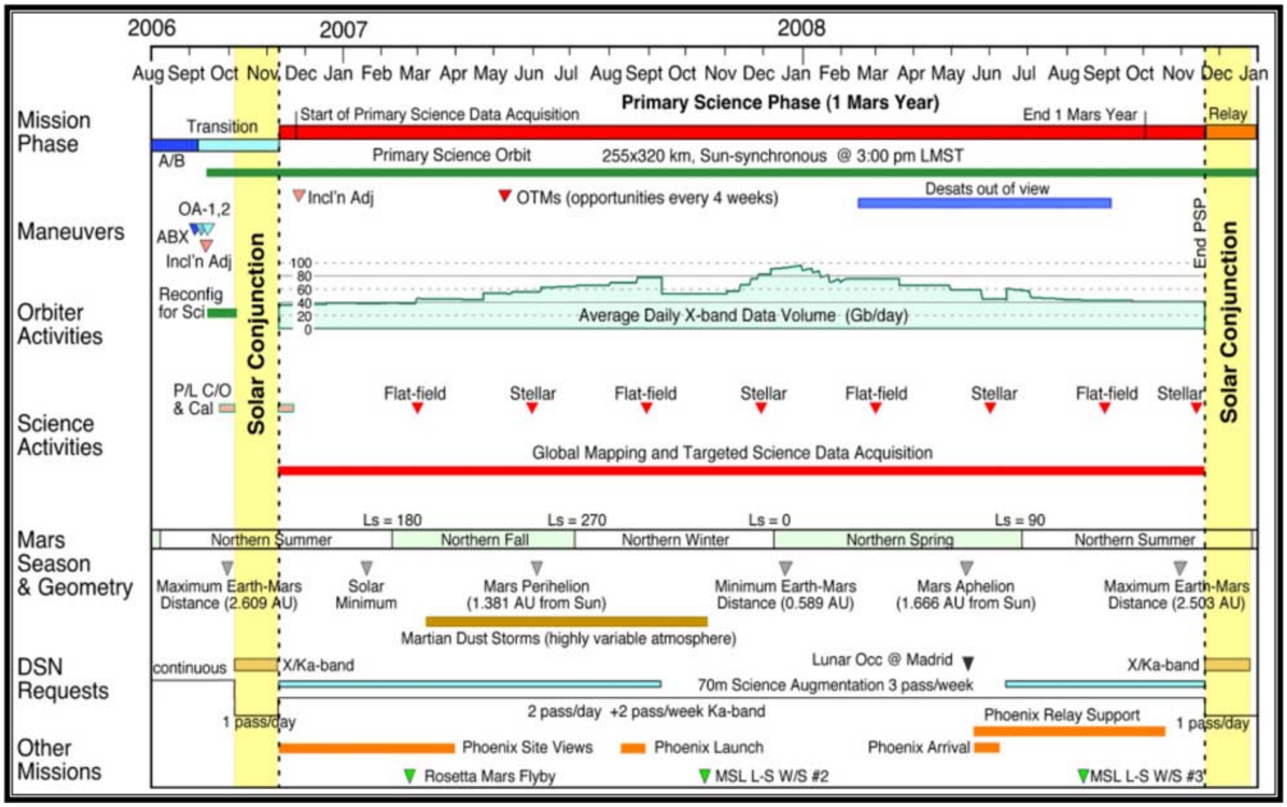

Figure 7. Activities during the primary science phase (PSP) are indicated. Timelines for the average daily X-band data volume return, for science calibration activities, and for DSN support are shown. Mars seasons (with areocentric longitude L_s) are indicated, as are key activities during the PSP by other missions. The latter includes the Mars Science Laboratory landing site workshops (MSL L-S W/S).

tions of the science instruments. The first science activity occurred 3 days after Launch (L + 3d) when the spacecraft panned the Mars Color Imager across the Earth and the Moon (the sunlit portions spanning 5 and 1 pixels, respectively, at the spacecraft range of 1 million kilometers). The next major science calibration was completed on L + 28d with the spacecraft slewing the nadir deck across the Moon and the Omega Centauri star cluster; both were imaged by HiRISE and CTX. Viewed at a range of 10 million kilometers, the Moon covered approximately 330 of the HiRISE 20,000 pixel swath and 17 of the CTX 5000 pixel swath. The focus on each instrument was judged to be good and, in fact, the best-guess position of the adjustable HiRISE focus mechanism was very close to the optimal setting.

[109] Other cruise activities included observations by the MCS instrument in September and December 2005 to assess darkening of its solar calibration target. Alignment of the HiRISE optical axis with the spacecraft star trackers and with CTX was confirmed. Calibrations conducted in December 2005 involved imaging stars with HiRISE and CTX to check changes in focus after out-gassing and to characterize further internal performance of the instruments. These cruise activities also included check-out of the telecommunications system and new records were set for the rate of data return from deep space via both the X-band and Ka-band systems.

[110] EMI tests were also conducted in which the SHARAD receiver was turned on and "listened" for EMI received through its folded antenna while various instruments and spacecraft subsystems were operating. Final characterization of EMI effects awaited deployment of the SHARAD antenna after aerobraking. In December 2005 and January 2006, CRISM demonstrated its ability to cool detectors to the desired operating values and performed a series of internal calibrations. Further calibration was conducted after deployment of the CRISM telescope cover on 27 September 2006.

[111] Instrument calibrations and focus will also be conducted during the primary science phase at periodic intervals (~6 months), and a final set of calibration observations will be taken in December 2008 after the end of the primary science phase.

5.1.2. Approach and Mars Orbit Insertion (MOI)

[112] No science calibrations were conducted in the last 50 days before orbit insertion. This time was devoted to precision navigation of the spacecraft in preparation for Mars orbit insertion (MOI) and to the demonstration by the Optical Navigation Camera (ONC) of precision navigation techniques for use by future missions. In the latter, imaging of the moons of Mars on approach provides a celestial clock that can be used to refine the spacecraft's location, thereby reducing the errors for a spacecraft entering the atmosphere on direct entry. Precise entry at the top of the atmosphere

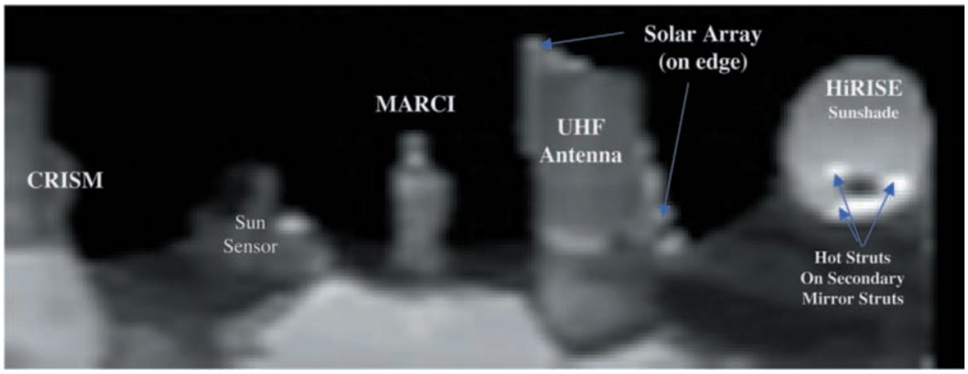

Figure 8. This self-portrait of MRO was taken by MCS on 25 March while in Mars orbit. MCS infrared radiances in the 32.5-micron channel were used to generate a grayscale mosaic of radiance emitted by the MRO payload deck. Taken near apoapsis on the tenth orbit after MOI, MCS scans covered ∼180° in azimuth as MCS verified intrusions into its field of view. The three bright spots within the HiRISE telescope opening (far right) are the arms supporting the (dark) secondary mirror. MARCI sits atop its pedestal (center), and the CRISM telescope is seen at the far left. The cylinder partially obscuring the solar array (in the +X direction, right of center) is a protective cover for the UHF antenna used by Electra for relay to spacecraft landed on Mars. (Image courtesy of D. McCleese and the MCS team; see *McCleese et al.* [2007]).

will reduce the size of the landing error ellipse or of the aerocapture corridor. During the last 10 days of approach, the critical sequence of ONC images were taken and replayed back to Earth after MOI. The information provided by ONC was not required by MRO for its own entry into Mars orbit, but was compared with the standard navigational techniques.

[113] On 10 March 2006, MRO fired its main thrusters in a 26-minute burn that slowed the orbiter enough that it was captured by Mars gravity into a 35-hour orbit. The initial orbit (Orbit 1) ended with a periapsis (P2) of 425 km following an apoapsis of 44000 km. The ONC data were replayed back to Earth and the spacecraft phase bits were reset, successfully concluding the seven-month journey from Earth to Mars. Results of the ONC technology demonstration looked promising, and preliminary analysis indicated improvements in the Deimos ephemeris.

5.1.3. Post-MOI Science

[114] The first weeks after Mars orbit insertion were spent reconstructing knowledge of the initial orbits, reconfiguring the spacecraft for aerobraking, and conducting an early imaging campaign. In this campaign, HiRISE, CTX, and MARCI took images of Mars over its southern midlatitudes on 23 and 25 March, during approach to periapses P10 and P11. Four HiRISE images, two CTX images, and one MARCI swath were taken on the approach to P10; five more HiRISE images were taken on the approach to P11, in part as a test for instrument disturbances ("jitter") that could smear the highest-resolution images. The altitude range for this early imaging was ∼4000 to 2000 km. Given the highly elliptical post-MOI orbit for MRO, this corresponded to that part of the orbit that had the proper ground speed for the cameras. This greater altitude, however, reduced spatial resolutions (but increased swath widths) by a factor of nearly ten from those to be taken from the Primary Science Orbit to be established at the end of aerobraking.

[115] The HiRISE and CTX line images taken at high latitudes were near the terminator (∼7:30 a.m. local time) and so had lower signal to noise. Furthermore, at this post-MOI local time, half the MARCI field-of-view looked westward at areas still in the predawn twilight. Despite these less than ideal conditions, the quality of the images was excellent overall [see *McEwen et al.*, 2007; *Malin et al.*, 2007]. This was particularly pleasing given that this was the first opportunity for the cameras to fill their fields of view completely and to test instrument settings against the real Mars. In particular, focus and thermal control were confirmed.

[116] Conducting the imaging campaign before the start of aerobraking provided a five-month period prior to the start of the PSP to fix any problems discovered with the instruments or with the spacecraft (e.g., an error in the spacecraft targeting software that caused altitude to not be properly accounted for when computing yaw compensation for planet rotation). It also tested the robustness of the end-to-end data transfer system.

[117] Near apoapsis A10 on 25 March, between the two sets of image taking, MCS was operated to provide a test of performance when viewing Mars. (MCS and MARCI operations at this time also provided a check of procedures that could have been used to monitor the Mars atmosphere for aerobraking, but this was not needed.) In addition to scanning across Mars [see *McCleese et al.*, 2007], MCS used its two-axis gimbal system to scan around the instrument deck to confirm its field of view with regard to spacecraft structures, including the other instruments on the nadir-pointing (+Z axis) deck. The result was a self-portrait of the MRO orbiter, now safely operating in Mars orbit (Figure 8).

5.2. Aerobraking

[118] Aerobraking is the fine art of flying the spacecraft deep enough into the atmosphere that the frictional drag of

the atmosphere on the spacecraft near periapsis is enough to bring apoapsis in from ~44000 to 460 km without significant fuel use and yet not so deep on any one orbit that frictional heating will damage the orbiter. Both the heating and the drag are proportional to atmospheric density, which decreases exponentially with height. Thus the right "balance" is achieved by small propulsive adjustments of the aerobraking orbits, nominally done at apoapsis, which place periapsis at the right altitude. Spacecraft accelerometers and tracking data provide the primary information needed to plan altitude adjustments during the aerobraking phase. Analysis of these same in situ measurements in greater depth form the basis of the first full science investigation planned for MRO. These analyses will provide key insights into upper atmospheric structure and into transport mechanisms affecting atmospheric escape at still higher altitudes (see section 3.8). Thus the MRO campaign of science investigation formally began with the aerobraking phase.

[119] As it approached each aerobraking periapsis, the spacecraft turned, using reaction wheels, from its nominal "vacuum-phase" attitude to its aeropass configuration. In this configuration the main thruster assembly was turned to the velocity vector, the solar arrays and the HGA were turned such that the backs of the panels and of the dish faced the flow, and the payload deck was pointed at right angles to the same flow. Following the drag pass, the spacecraft reoriented itself so that its body and HGA pointed at Earth with the solar arrays off-pointed to the Sun. This reorientation of the spacecraft occurred on each of 430 aeropasses. For most of aerobraking the periapsis altitudes were in the 100–110 km altitude range. Without aerobraking, an additional 400 kg of fuel would have been required to establish the primary science orbit by propulsion alone.

[120] The primary concern for aerobraking is the natural variability of the density of the upper atmosphere at these altitudes. In particular, previous aerobraking missions have shown that regional and planet-encircling dust storms will heat the lower atmosphere either directly through the absorption of solar radiation by the airborne dust or indirectly by the expansion of the cross-equatorial circulation. This heating causes higher densities at greater altitudes as the compressible atmosphere expands. In the case of dynamical heating, even a regional dust storm in the opposite hemisphere can produce a significant effect at the periapsis of the aerobraking spacecraft [*Keating et al.*, 1998]. The larger storms (in size and duration) are of greatest concern because they have the greatest vertical extent; more local dust storms have smaller vertical extents and therefore less effect on the aerobraking altitudes. Fortunately, the larger storms are rare in the northern spring and early summer seasons when MRO aerobraking took place [*Zurek and Martin*, 1993]; local storms, of course, have been observed in all seasons [*Cantor et al.*, 2001]. As a precaution, however, Mars Global Surveyor and Mars Odyssey instruments (MOC, TES, THEMIS) provided daily monitoring of the lower Martian atmosphere in order to detect events. While seasonal local storms were observed, none were large enough to substantially perturb aerobraking operations.

[121] Over the five-month period from 5 April through 30 August, the periapsis of the aerobraking orbits moved from 70S on the night side of the planet, past the winter south pole, ending up near the equator in very early morning. The aerobraking profile was designed so that apoapsis decreased to ~460 km as the orbit plane moves to a local mean solar time of 3 p.m. to 3 a.m. In fact, the duration of the aerobraking phase was set by how long it takes Mars to move around the Sun, so that the local solar time of the orbiter's inertial plane evolved from the arrival 8:35 p.m. to the desired ~3 p.m. for the primary science orbit. On 30 August the orbiter used its mid-sized thrusters to raise periapsis out of the atmosphere and thereby terminate the aerobraking phase.

5.3. Transition

[122] Aerobraking ended eight weeks prior to solar conjunction. The propulsive maneuver that terminated aerobraking raised periapsis above 200 km where atmospheric drag is greatly reduced. In September 2006, a series of propulsive maneuvers raised periapsis further, lowered apoapsis and trimmed the orbit inclination to establish MRO in the desired repeating, near-circular, near-polar primary science orbit. The final trim maneuvers adjusted the orbit inclination such that the drift of the orbit in inertial space compensates for the (mean) motion of Mars and thereby fixes the local mean solar time close to 3 p.m.

5.3.1. Preparations for Primary Science Phase Observations

[123] After conducting a final calibration of the pointing of the High-Gain Antenna, the next major event was the deployment of the 10-meter SHARAD radar antenna and of the CRISM telescope cover. Removal of a thermal cover and tie-down restraints released in succession the two 5-meter folded arms of the SHARAD antenna. Once released, the arms unfurled, propelled by the natural tension of the tubes carrying the wires that constitute the radar antenna. With the antenna deployed on 16 September, the full instrument was checked out two days later in both receive and transmit modes. Full calibration of SHARAD, including potential interference effects of different solar array positions, will be conducted during the early Primary Science Phase.

[124] Following the SHARAD functional checkout, the spacecraft established its nominal nadir-down orientation with the payload deck (+Z axis) pointing vertically down to a Mars reference ellipsoid (3-axis, with 2 equal equatorial axes). In late September the cover that had shielded the CRISM instrument optical path since launch was deployed. During solar conjunction, CRISM conducted a full decontamination heating cycle, now that its cover was open to space.

[125] To test observational procedures, the spacecraft and its payload took observations over several days, conducting both nadir and off-nadir (spacecraft-targeted) observations. Initially, the spacecraft operated all instruments in nadir-view modes; it then used its Integrated Target List (ITL) onboard software to point the instrument deck off-nadir at a series of targets while articulating the solar arrays and high-gain antenna as required for the primary science phase. The final week-long checkout was successful and provided an early look at a few high-priority targets (e.g., the candidate landing site for Phoenix and the Victoria Crater site with the Opportunity rover) prior to the start of the Primary Science Phase after solar conjunction.

5.3.2. Solar Conjunction

[126] Solar conjunction is a period when spacecraft communications can be disrupted by passage through the Sun's near field, particularly given that Mars is close to its maximum range from Earth. For this reason, a command moratorium is set in place for when the Earth-Sun-Mars angle $\leq 3°$, based on previous experience with the X-band telecom system. Solar conjunction itself is defined conservatively as the period when this angle $\leq 5°$ (7 October to 8 November 2006). During this period the orbiter is restricted to nadir pointing.

[127] Although not considered a mission phase, MRO conducted limited science during solar conjunction, which occurred this year during mid-northern summer on Mars. This is a period when water vapor released into the atmosphere over high northern latitudes during northern spring and early summer [*Jakosky and Farmer*, 1982] is moving southward while recondensing in the north polar regions. MRO began its characterization of the Martian atmosphere's seasonal variations by operating the MCS and MARCI instruments during this period. Both instruments are designed to operate primarily in the spacecraft's nadir-reference mode, and both are designed to observe water vapor (MCS) or its ozone surrogate (MARCI). These early observations, which are still being analyzed, captured a key period in the water cycle and will provide a proper closure of the annual cycle given similar observations at the end of the PSP. Given some overlap, one can ensure that differences at the beginning and end of the Mars year are due to Mars and not to instrumental artifacts. The start of observations at $L_s \sim 115°$, instead of 130°, also provides atmospheric characterization of the Phoenix landing site latitudes at a time closer to the season of their arrival ($L_s \sim 80°$) almost one Mars year later. (The areocentric longitude of the Sun, L_s, is used to indicate seasonal date with 360° spanning a Mars year and each season spanning 90°, starting with northern spring equinox at $L_s = 0°$.)

5.4. Primary Science Phase (PSP)

[128] The PSP began 7 November 2006 (Ls ~ 132) and continues until 18 November 2008 (Ls ~ 160), just before the second solar conjunction period (18 November to 24 December 2008). During this one Mars year the MRO instruments will monitor the seasonal variation of the atmosphere (MARCI, MCS, CRISM) and of atmospheric phenomena (CTX, HiRISE), will probe the subsurface to reveal layering and the possible presence of ice (SHARAD), will explore the composition and structure of the permanent and seasonal ice caps (CRISM, MARCI, CTX, HiRISE, SHARAD), the energy balance and mass exchange of the seasonal polar caps (MCS, MARCI, CRISM, Gravity), the composition and structure of the surface (CRISM and HiRISE, CTX) and of the subsurface (SHARAD, Gravity).

[129] During early PSP, data return rates are relatively low (section 4.3) and the number of locales targeted at the highest spatial resolutions will be somewhat limited. During this period some orbits will be reserved (i.e., restricted to nadir viewing) to build up regional coverage by CRISM and to provide global coverage of atmospheric phenomena (e.g., the release of water from the summertime residual north polar cap).

[130] The number of targeted locales is expected to increase as Earth catches up with Mars and reduces the range for telecommunications. Assuming nominal operations, several thousand locales will be targeted by HiRISE, CRISM or CTX and their various combinations over the two Earth years of the PSP.

[131] Stereo observations by HiRISE or CTX require two independently scheduled targeted observations. The first image of a stereo pair will often be taken at low roll angles (i.e., close to nadir) and examined to see if the site is sufficiently interesting to take the second, higher phase angle image. Approximately 1000 stereo pairs are planned for HiRISE alone during the PSP.

5.4.1. Coordinated Observations

[132] Each high-resolution targeted image by HiRISE or CRISM will have a CTX context image. For many targets HiRISE and CRISM will have "ride-along" observations with one another and with CTX. Figure 9 illustrates how the spatial coverage of the various instruments may overlap for a targeted observation.

5.4.2. Data Products and Archive

[133] Processing of the data is the responsibility of the individual instrument and facility science teams at their designated facilities. Typically, processing of orbiter remote sensing observations produces data products that expand by a factor of ten or more over the originally acquired data volumes due to decompression, appending ancillary data, calibration, and oftentimes map projection.

[134] Table 5 shows the presently defined data products for the eight MRO science investigations. Included there are both standard and special products. Special products are characterized principally by the need to conduct preliminary analyses of the data (using standard products and in-flight calibrations) in order to define and implement the final processing steps. This dependency on the analysis of in-flight data even while the science teams must keep up with the nominal planning activities and standard product processing means that special products are generated sporadically or even only at the end of the PSP. Other products may be delivered periodically because they require data that have extended coverage in space and time (e.g., certain map products might be delivered on six month centers).

[135] The nominal schedule for product delivery to the PDS is that every three months data acquired 6–9 months ago and the high-level products derived from them will be released to the PDS discipline nodes. The first such release is scheduled for May 2007, and will cover the first 3 months of data acquired in the PSP. An exception to this is the delivery of accelerometer data acquired during aerobraking, since the Accelerometer team's first priority during that period was to support safe operation of the spacecraft on its many passes through the upper atmosphere. The "quick-look" data products needed for operations do not have the quality control needed for detailed scientific analysis and so the products will be systematically regenerated, now that aerobraking operations have ended.

[136] On the basis of past experience, it is anticipated that many standard products will need to be reprocessed as calibrations are updated during the mission and as instrument artifacts and spacecraft influences are better understood (this is indicated in Table 5 by "Nominal + EOSM"). Reprocessing at the end of the science mission (EOSM) will

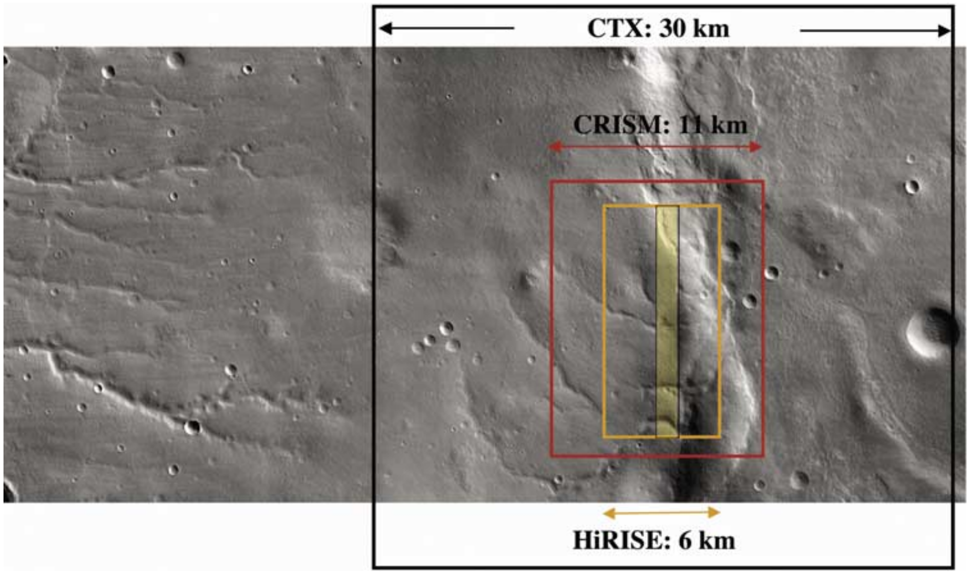

Figure 9. Potential coverage by MRO instruments during coordinated targeted images. In the PSP the spacecraft motion would be from bottom to top. The shaded box also indicates potential HiRISE color coverage. Cross-track dimensions assume the full instrumental swath; downtrack dimensions reflect data volume considerations. The background image is the first image taken by HiRISE during the post-MOI imaging activity; the image was taken at ~7:30 a.m. local time, with the Sun to the upper right and at a range of ~2500 km, so that the resolution is ~2.5 m/pixel, ~9 times the resolution possible in the PSP (image courtesy of A. McEwen and the HiRISE team; see *McEwen et al.* [2007]). The brightly lit ridge and surrounding terrain are in the Bosporos Planum (~34S, 305E) northwest of the giant Argyre impact basin.

also take advantage of the final set of calibrations conducted after PSP in December 2008. Final processing of the last science data acquired, any reprocessing of earlier data, and all data deliveries to PDS are to be accomplished by July 2009.

[137] In the following subsections, note that, for site selection, MRO is funded to acquire the data and produce its basic products. Special products or further analysis are the responsibility of the requesting project.

5.4.3. Phoenix Support

[138] Early in the PSP, observations by the MRO instruments of potential landing ellipses in the Phoenix landing zone are a high priority as these areas are rapidly moving into twilight and polar night conditions (including polar "hoods" of condensate clouds) as northern summer wanes. The objective of these observations is to certify that these areas are safe and that the prime sites are the best for scientific exploration.

[139] As Phoenix approaches entry into the Mars atmosphere in May 2008, MRO will use MARCI and MCS to monitor atmospheric conditions and use HiRISE, CTX, CRISM and SHARAD data to examine for any changes in the prime and backup landing ellipses.

[140] Phoenix arrives at its high northern latitude site in May–June of 2008 and will operate on the surface for up to 90 sols before cooling temperatures and polar twilight ends its landed operations. After Phoenix is safely on the surface, MRO will provide up to two contacts a day for relay and will help monitor atmospheric conditions, particularly the overhead dust opacity, to aid Phoenix operations on the surface. The two projects will also carry out a campaign of simultaneous observations.

5.4.4. Mars Science Laboratory (MSL) Support: Site Selection

[141] Site selection for MSL, which launches in the fall of 2009, began with a workshop in May 2006. At that time a NASA organized science community workshop selected a prioritized list of ~40 sites for MRO to observe. This list will evolve as observations of the highest priority sites are acquired and new candidate sites are identified from data acquired by MRO and other Mars missions. In subsequent workshops the number of potential landing sites for MSL will be reduced to a few (<10). These sites will be thoroughly observed using all the MRO, MGS, ODY and Mars Express capabilities to help assure that the best site is chosen for MSL prior to its launch.

5.4.5. Mars Exploration Rover (MER) Sites

[142] Observations by MRO of the MER sites have high priority early in the PSP since these provide the most extensive "ground truth" for interpreting the MRO remote sensing data. A campaign of simultaneous observations by MRO and the MER craft may also be conducted, especially with MER instruments that can look up from the surface. High-spatial-resolution data from MRO are helpful in planning new traverses by the MER craft, and atmospheric data returned by MRO can help monitor atmospheric dust opacity, which affects power generation by the rovers.

5.4.6. End of Primary Science Phase

[143] Observations with the MRO science instruments nominally end by December 2008, prior to the second solar conjunction. The science teams are funded for an additional

Table 5. MRO Science Data Products and Delivery Schedule[a]

Investigation	Science Data Product	NASA Level	Delivery Schedule	Estimated Vol., Gb
ACCEL	EDR: Raw Telemetry Data	0	March 2007	<1
ACCEL	Density, Density Scale Height	2	June, Sept. 2007	1
ACCEL	T, P, Scale Heights, 1.26 nbar heights	3	September 2007	TBD
CTX	EDR: Raw image data with calibration data and ancillary information	0	Nominal[b]	3,400
CRISM	EDR: Raw spectral cubes with pointing, time planes	0	Nominal	12,800
CRISM	Calibrated targeted and Emission Phase Function spectra cubes with pointing, geometric, and physical properties data	1A, 3	Nominal + EOSM	59,000
CRISM	In-flight and ground calibration files	3, 2	Nominal + EOSM	1,200
CRISM	Spectral Library	2	Available	1
CRISM	Map-Projected multispectral cubes (calibrated radiances, surface spectra, spectral indices in map projected, tiled cubes)	1B	Periodic + EOSM	90,000
CRISM	Selected Targeted Observations reduced to surface spectral image cubes and map projected (~50 sites)	2, 3	Periodic + EOSM	3,500
Gravity	TRK-2-34 Files	0	Nominal	7
Gravity	Harmonic expansion coefficients of gravity field; error co-variances; Mapped products (e.g., aeroid)	3	Periodic + EOSM	50
HiRISE	EDR: Raw Image Data	0	Nominal	12,100
HiRISE	Panchromatic Images, (merged) Color Images, Binned (2 × 2) Stereo	1C	Nominal + EOSM	60,000
HiRISE	Digital Elevation Models	3	EOSM	1,000
MARCI	EDR: Raw Image Data	0	Nominal	1,300
MCS	EDR: Unpacked telemetry data	1A	Nominal	640
MCS	Calibrated Radiances	1B,1C	Nominal	1,300
MCS	Atmospheric Profiles, Column abundances	2	Periodic + EOSM	350
MCS	Mapped monthly meteorological fields	3	Periodic + EOSM	TBD
SHARAD	EDR: Raw data	1A	Nominal	5,000
SHARAD	RDR: Filtered, compressed, calibrated profiles	1B	Nominal	3,200
SHARAD	Radar-grams and derived products	2, 3	Periodic + EOSM	TBD

[a] Based on the MRO Project Data Archive Generation, Validation, and Transfer Plan (JPL D-22246). EOSM: End of science mission (30 June 2009), six months after the end of data taking in PSP.

[b] Releases to PDS every 3 months starting in May 2007, each containing data acquired 6–9 months previously.

six months to process and archive the final data, to carry out any reprocessing of earlier data products as required, and to complete and archive all special data products. No science activities are currently funded beyond fiscal year 2009.

5.5. Relay

[144] MRO is required to support science observations for one Mars year and to support relay for missions launched in the 2007 and 2009 launch opportunities. Originally, these activities were envisioned to occur in two phases, with the relay phase beginning in December 2008 and extending until the nominal end of the MRO mission on 31 December 2010. This definition was made before the selection of the Phoenix Mars Scout lander mission for the 2007 opportunity and of the Mars Science Laboratory (MSL) rover for the 2009 opportunity. As noted above, relay support for the Phoenix mission will occur during the latter part of the PSP and before the nominal relay phase. ODY and MRO will share relay responsibilities for Phoenix.

[145] MSL lands on Mars in the fall of 2010. Since it is projected to have a one Mars year primary science phase, it is likely that MRO support will continue past the nominal end of the MRO mission.

[146] The Electra UHF telecommunication package has the flexibility to support relay for both the Phoenix lander and the Mars Science Laboratory. Relay by MRO also includes return of signals from Phoenix and MSL during their respective critical entry, descent and landing sequences. MRO will do this without changing its orbital plane, but will phase its position in that orbit for optimum viewing.

[147] It is likely that MRO, like its successful predecessors, will conduct an extended mission of science observations during this Relay phase. The instruments have no consumables; the major lifetime concerns during development were the MCS scanning mechanisms and the mechanical devices used to cool the CRISM focal plane detectors. (CRISM has 3 such coolers, only one of which is needed at any given time). These units all passed their PSP lifetime tests. Thus it is likely that several, perhaps all, instruments could be used during the relay phase.

[148] Continued science operations could provide the same near-real time monitoring of the atmosphere for MSL as is currently planned for Phoenix. Additional high-resolution imaging by MRO could be useful in planning traverses for the MSL rover.

[149] In anticipation of the need for continued relay support beyond 2010 and for science instrument observations past 2008, MRO was required to have sufficient fuel to continue science observations from the PSO until December 2010 and to support relay for a few years after 2010,

perhaps from a higher orbit. In fact, the fuel reserves added just before launch could extend operations in the low-altitude PSO until 2014. Thus an extended science mission could be conducted without compromising the PSP spatial resolutions. (Note that MRO does not need to move to a higher orbit for planetary protection, as analysis has shown that the bioburden surviving the orbiter's burn-up in the event of an uncontrolled atmospheric entry meets the required limit.)

6. Science Planning Process

[150] As discussed in section 4, the observation goals for MRO are facilitated by mission design and spacecraft capability. However, the MRO observational program is a very ambitious one, and several key factors have shaped the science planning process. The low PSO altitude results in greater atmospheric drag and thus greater uncertainty in orbit prediction and a shorter planning horizon for targeted observations. MRO's high data rate means that the observing timeline will be very full, and yet the data volumes inherent in high-resolution observing necessitate a certain spacing of targeted observations.

[151] Operations during the PSP must also reconcile three observation modes: global monitoring, regional survey, and observations of local targets, including stereo. Here, "targeted observing or imaging" describes viewing specific, localized areas ($\sim$30–1000 km^2) on the planet typically near, but not necessarily on, the ground track beneath the spacecraft. A major challenge to MRO operations is to determine which off-nadir targets to observe by which instruments on what orbit. Typically off-nadir images will be reserved for high-priority and time-critical observations, as they require a significant portion of an orbit, up to 20 minutes, to accomplish; during that time the spacecraft nadir point may have moved up to 60° of latitude. The science observation planning process for MRO is designed to optimize the competing interests of the six different instruments in various versions of these three operating modes.

6.1. Accommodating Observing Modes

[152] The pointing objectives for each instrument are carried out through a combination of nadir pointing and off-nadir rolls. Since the MCS limb observations are compromised when the spacecraft tilts their vertical detector array by rolling off-nadir by more than 9°, a series of guidelines were formulated to limit the number of large rolls (i.e., rolls > 9°) in a given time or spatial window. In a compromise MCS accepts some gores in its coverage, while targeted observations are spread out over more opportunities and are somewhat limited in number from what would be permitted by the data return rate alone.

[153] To help the planning process, the following "MCS Rules" were adopted: Generally, no more than 1 large roll on any orbit, no large rolls on adjacent orbits and no more than 4 large rolls per day. The other interruptions to MCS are the "freeze modes" which enable jitter-free very-high-resolution imaging and here the guidelines are an interval of at least 5 minutes between one freeze and the start of another, and no more than 4 such freezes in an orbit. These limitations are not as onerous as they might seem, given that the number of off-nadir targets is limited by practical considerations to no more than 4 per orbit and more typically just two. Also, the 17-day repeat cycle provides multiple opportunities to view a given target with a smaller roll by the spacecraft. The rules do impact stereo coverage and the desire to see time-dependent phenomena at a particular place at a particular time. Thus the rules can be appealed in the TAG meeting that is part of the process for planning interactive observations, but generally the number of targeted observations in contention will be small. Typically off-nadir rolls will be small with large angle rolls (>9°) allocated to either stereo observations, which require a look angle separation of 15–20°, or time critical observations.

[154] Like atmospheric monitoring, regional survey of the surface also prefers extended periods of nadir observations, thereby reducing the number of gaps in the coverage that must then be filled at a later date by targeted observing. SHARAD, CRISM, and CTX each operate in a regional survey mode, in which they observe during extended portions of an orbit. Although SHARAD can operate day or night, planning SHARAD passes for the night side produces a more evenly distributed data acquisition load for the payload overall. This also removes any possibility of ionospheric interference with the radar signal, although interference is expected to be quite small in its 15–25 MHz receive band. SHARAD has also been allocated 400 dayside passes over the course of the mission to allow for continuous passes over the poles to characterize the seasonal and permanent polar ice caps.

[155] Early in the mission CRISM will conduct a campaign of multispectral mapping via nadir imaging in selected bands on every other orbit. Like the MCS rules, a set of guidelines has been formulated for the CRISM coverage. For example, the survey orbit could be switched to an adjacent orbit to accommodate a high-priority targeted observation. The early emphasis on nadir observations allows CRISM to cover a large fraction of the globe at moderate resolution early in the mission for use in targeting higher-resolution imaging later in the mission. This focus also benefits MCS monitoring of the water cycle (see above), and its impact on targeted observations is relatively low because the limited data rates early in PSP already constrain the number of high-resolution images that can be acquired. In the second half of the PSP, when data rates are at their maximum, more targeted observations will be planned.

[156] HiRISE, CRISM and CTX are most concerned with observing targeted locales. Furthermore, some of the best science from MRO may well result when HIRISE, CRISM, and CTX all acquire simultaneous images of the same target (see Figure 9). Planning coordinated images is challenging because it requires interactions between 2 or more teams during a relatively short segment of each planning period. Because of their high scientific potential, coordinated images are given priority in the planning process. Individual team targeted observations then have to be folded into the Integrated Target List in a way that they do not conflict with the designated exclusion zones, high priority targets (including coordinated targets), or each other.

6.2. Planning Horizon

[157] A disadvantage of the low-altitude orbit of MRO is that atmospheric drag will be greater than MGS or ODY

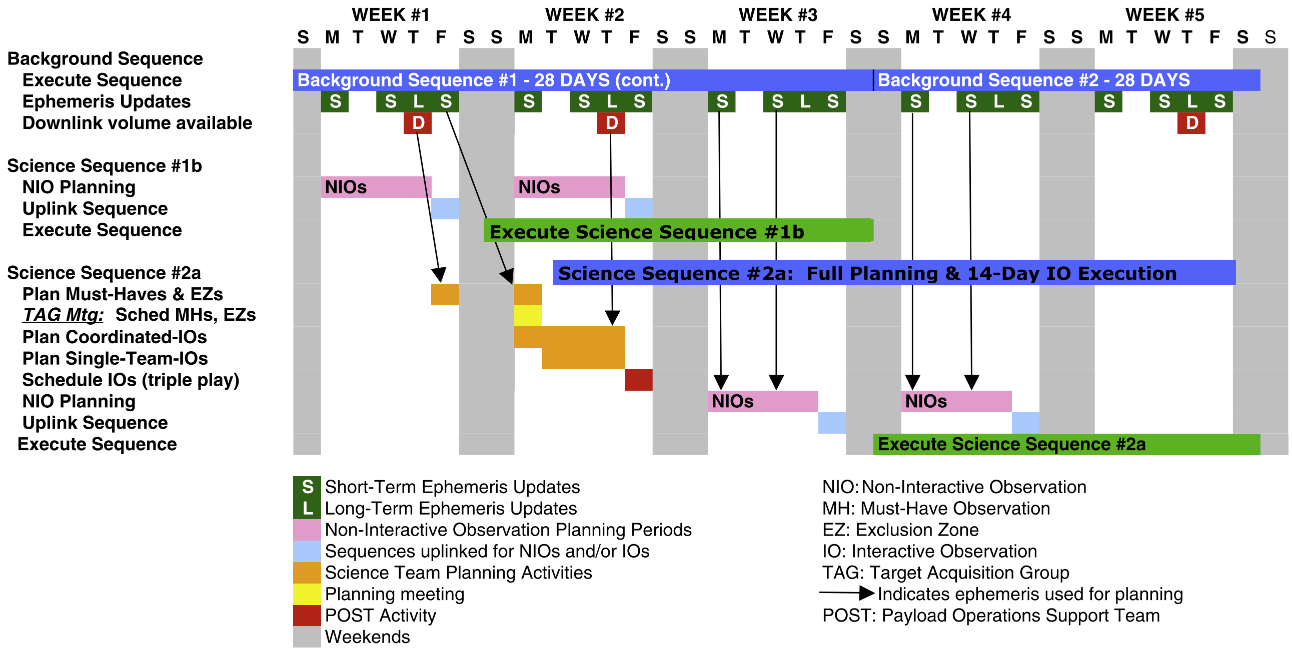

Figure 10. Science planning process covering one month of a background sequence, which itself spans two (2-week) planning periods.

have experienced. The greater atmospheric effects mean that the orbit predictions can be used to plan off-nadir roll angles only up to 30 days in advance; locations on the ground track can only be planned up to 2 weeks in advance if the downtrack errors are to be kept to 1 km. Fortunately, the drag effects are lowest near Mars aphelion and greatest around perihelion, as atmospheric density at a given altitude decreases or increases annually as the atmosphere below reaches its seasonal minimum or maximum temperatures. (Because of the great altitude of the orbit, this hydrostatic effect tends to dominate the effects of topography and of the semi-annual variation of atmospheric mass.) Thus the targeting predictability will be better at the start of the PSP (in the midst of northern summer) when procedures are first being used. This planning horizon dictates a 2-week science operations planning cycle, against the traditional monthlong (4-week) background spacecraft and telecom planning sequence. The planning process is illustrated in Figure 10, and discussed in detail in the next section.

6.3. Science Planning Cycle

[158] Interweaving these differing objectives into a plan for acquisition of 40–180 Gb of data per day is challenging because it requires thoughtful interaction in the two-week planning cycle dictated by the ephemeris error growth due to atmospheric drag. To plan all the activities simultaneously is not efficient. Thus a sequential approach has been developed and tested (Figure 10).

[159] Interactive observations are planned for a 2-week observing period. The planning process begins once the background spacecraft activities (e.g., thruster activity to unload the momentum wheels) are identified, downlink volumes are computed on the basis of planned DSN station contacts, and a long-range (covering 4 weeks) ephemeris is available. This information is available on the Thursday two weeks prior to the execution of a given science sequence.

[160] The planning process then distinguishes between non-interactive and interactive observations. By definition, Non-Interactive Observations (NIOs) do not require a change in the operations of other instruments or off-nadir pointing by the spacecraft; thus they are always nadir observations. Conversely, Interactive Observations (IOs) are typically off-nadir observations, but can also be nadir observations that require a change in another instrument's observing mode. A primary example of the latter is a nadir, high-resolution HiRISE image that requires very high stability. In this case, the spacecraft software may pause MCS scanning and solar array motions while HiRISE is imaging.

[161] NIOs are planned on a weekly basis to allow for the most up-to-date ephemeris. During each week, these non-interactive observations are planned on top of a previously prepared sequence that describes the interactive observations (IOs) for that week.

[162] The first step in planning IOs (see steps in Science Sequence #2a in Figure 10) is to plan "Must-Have" (MH) observations and exclusion zones (EZs). MHs are very high priority targets, such as the Phoenix landing site or time-critical observations. Examples include viewing a particular place at a particular seasonal date or obtaining the second image in a stereo pair in a timely manner. Exclusion zones are periods (portions of the ground track) when off-nadir targets are prohibited; these allow teams to carry out regional surveys. These two types of observations are approved in bi-weekly meetings of the Target Acquisition Group (TAG), which consists of the MRO Project Science Group (PSG) and appropriate representatives from other projects (e.g., MSL). The TAG is currently scheduled for every other Monday (Figure 10) and is chaired by the MRO Project and Deputy Project Scientists. (Other members of

the PSG include the MRO Principal Investigators, Team Leaders, and the MRO Program Scientist.)

[163] Off-nadir coordinated targets are given the next highest priority. Every other Wednesday teams exchange lists of potential coordinated IOs for the upcoming two-week implementation period. On Thursday teams deliver an integrated list of those observations they have decided to observe jointly (coordinated IOs) and those observations requested by a single team. These images are then scheduled in a round robin manner, with coordinated images having priority. Once coordinated targets are scheduled, CRISM, CTX and HIRISE plan additional single team off-nadir images. Each team has an allocation for off-nadir images over the course of the mission to prevent the entire time line from being taken up with off-nadir imaging. A final step in the off-nadir planning process allows teams to piggyback their own images onto single team, off-nadir images scheduled by other instruments. This increases the number of coordinated IOs without taking more of the planning timeline.

[164] The spacecraft uses the latest available ephemeris that has been uploaded to update the pointing for off-nadir IO observations, thus allowing the IO planning process to occur every other week. Planning for nadir NIO observations must occur weekly to ensure sufficient ephemeris accuracy to correctly time nadir targeted images. In Figure 10 the full cycle for a sequence labeled #2a is shown. The planning for this sequence occurs while the prior sequence, #1b is being executed.

[165] Long-term planning is accomplished at Project Science Group meetings 3–4 times a year. In addition to the 2-week planning cycle, the Project Science Group conducts longer term planning as part of its quarterly meeting schedule. Progress on achieving the mission objectives, including landing site characterization and verification, will be reviewed, and decisions on the proper mix of observing objectives such as surveys, stereo imaging, coordinated images, and landing site coverage will be made.

[166] This process evolved significantly during the MRO development phase, reflecting the experience of many science team members and the unique flavor of the MRO mission, with its combination of observing modes and emphasis on coordinated imaging. This process was further refined during two Operations Readiness Tests prior to PSP and will no doubt be refined as more experience is gained in the Primary Science Phase itself.

7. Summary

[167] The NASA Mars Exploration Program has defined the following criteria to be met if MRO is to achieve full mission success:

[168] 1. Operate the orbiter and all six instruments in the PSO in targeting, survey and mapping modes, as appropriate, over one Mars year; conduct the facility science gravity and accelerometer investigations.

[169] 2. Return representative data sets for each instrument for a total science data volume return of 26 Tb or more. Included in the returned data volume shall be information describing hundreds of globally distributed targets.

[170] 3. Process, analyze, interpret, and release data in a timely manner, including archival of acquired data and standard data products in the PDS within 6 months of acquisition.

[171] 4. Conduct relay operations for U.S. spacecraft launched to Mars in the 2007 and 2009 opportunities.

[172] According to the agreement with the MEP, minimum mission success for MRO could still be achieved if one or more instruments failed. The floor established was the return of 10 Tb of science data from HiRISE and CRISM or from their combined operations, plus 5 Tb from at least 3 of the 4 other instruments (CTX, MARCI, MCS, SHARAD).

[173] These metrics were established to provide quantifiable measures of success. They reflect the measurement objectives of extending the present atmospheric climatological record, of achieving the resolution and coverage needed to find those places on Mars best able to show us how Mars has changed over time and in particular the role of water on its surface, and of extending a new thrust into exploring the subsurface of the planet. To do this systematically requires the major increase in the volume of data that MRO will provide. Thus the success criteria specify particular volumes of data, even though improvements in understanding are not simply linear with the number of bits; major new discoveries can come at any time. The emphasis on early release to the broader science community recognizes the challenge of fully analyzing the enormous volumes of data and of fully exploiting the different data streams to address the fundamental questions regarding Mars.

[174] The data that MRO acquires and that its science teams process, release, and analyze will advance our understanding of how Mars has evolved over time and what processes were active in the past and which are active today. The MRO data will also help identify the most promising sites for future missions to explore by landing, by roving and perhaps by sample return. As part of the National Vision for Space Exploration, these same data will support planning of human missions to Mars.

[175] The ability of the Mars Reconnaissance Orbiter to operate its instruments in their various observing modes, to coordinate their measurements, and to return the order of magnitude more data that they will generate will enable, as its name implies, a thorough reconnaissance of the planet and a storehouse of data that will be mined for years to come.

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References

Bibring, J., et al. (2005), Mars surface diversity as revealed by the OMEGA/Mars Express Observations, *Science*, *307*, 1576–1581, doi:10.1126/science.1108806.

Bougher, S. W., J. R. Murphy, J. M. Bell, and R. W. Zurek (2006), Prediction of the structure of the Martian upper atmosphere for the Mars Reconnaissance Orbiter (MRO) mission, *Mars*, *2*, 10–20, doi:10.1555/mars.2006.0002.

Boynton, W. V., et al. (2002), Distribution of hydrogen in the near-surface of Mars: Evidence for subsurface ice deposits, *Science*, *297*, 81–85, doi:10.1126/science.1073722.

Cantor, B. A., P. B. James, M. Caplinger, and M. J. Wolff (2001), Martian dust storms: 1999 Mars Orbiter Camera observations, *J. Geophys. Res.*, *106*, 23,653–23,687.

Grant, J. (Ed.) (2006), Mars scientific goals, objectives, investigations, and priorities, 31 pp., white paper, Mars Explor. Program Anal. Group (MEPAG), Jet Propul. Lab., Pasadena, Calif. (Available at http://mepag.jpl.nasa.gov/reports/index.html)

Greeley, R. (Ed.) (2001), *Science Planning for Exploring Mars, Part 2, Scientific Goals, Objectives, Investigations, and Priorities*, *Jet Propul. Lab. Publ. 01–7*, Jet Propul. Lab., Calif. Inst. of Technol., Pasadena, Calif.

Jakosky, B. M., and C. B. Farmer (1982), The seasonal and global behavior of water vapor in the Mars atmosphere: Complete global results of the Viking atmospheric water detector experiment, *J. Geophys. Res.*, *87*, 2999–3019.

Keating, G. M., et al. (1998), The structure of the upper atmosphere of Mars: In situ accelerometer measurements from Mars Global Surveyor, *Science*, *279*, 1672–1676.

Malin, M., J. F. Bell III, W. Calvin, R. T. Clancy, R. M. Haberle, P. B. James, S. W. Lee, P. C. Thomas, and M. A. Caplinger (2001), The Mars Color Imager (MARCI) on the Mars Climate Orbiter, *J. Geophys. Res.*, *106*, 17,651–17,672.

Malin, M. C., et al. (2007), Context Camera Investigation on board the Mars Reconnaissance Orbiter, *J. Geophys. Res.*, doi:10.1029/2006JE002808, in press.

McCleese, D. J., R. D. Haskins, J. T. Schofield, R. W. Zurek, C. B. Leovy, D. A. Paige, and F. W. Taylor (1992), Atmosphere and climate studies of Mars using the Mars Observer pressure modulator, *J. Geophys. Res.*, *97*, 7735–7757.

McCleese, D. J., J. T. Schofield, F. W. Taylor, S. B. Calcutt, M. C. Foote, D. M. Kass, C. B. Leovy, D. A. Paige, P. L. Read, and R. W. Zurek (2007), Mars Climate Sounder: An investigation of thermal and water vapor structure, dust and condensate distributions in the atmosphere, and energy balance of the polar regions, *J. Geophys. Res.*, doi:10.1029/2006JE002790, in press.

McEwen, A. S., et al. (2007), Mars Reconnaissance Orbiter's High Resolution Imaging Science Experiment (HiRISE), *J. Geophys. Res.*, doi:10.1029/2005JE002605, in press.

Muhleman, D. O., A. W. Grossman, B. J. Butler, and M. A. Slade (1991), Radar images of Mars, *Science*, *253*, 1508–1513.

Murchie, S., et al. (2007), Compact Reconnaissance Imaging Spectrometer for Mars on Mars Reconnaissance Orbiter, *J. Geophys. Res.*, doi:10.1029/2006JE002682, in press.

NASA (2001), Announcement of Opportunity, Mars Reconnaissance Orbiter—2005, *AO 01-OSS-02*, Washington, D. C., 6 Jun.

NASA (2004), *The Vision for Space Exploration*, *NP-2004-01-334-HQ*, 23 pp., Washington, D. C.

Picardi, G., et al. (2005), Radar soundings of the subsurface of Mars, *Science*, *310*, 1925–1928.

Seu, R., et al. (2007), SHARAD sounding radar on the Mars Reconnaissance Obiter, *J. Geophys. Res.*, doi:10.1029/2006JE002745, in press.

Shambayati, S., D. Morabito, J. S. Border, F. Davarian, D. K. Lee, R. Mendoza, M. Britcliffe, and S. Weinreb (2006), Mars Reconnaissance Orbiter Ka-band (32 GHz) demonstration: Cruise phase operations, paper presented at AIAA SpaceOps Conference, Am. Inst. of Aeronaut. and Astronaut., Rome.

Shambayati, S., J. S. Border, D. D. Morabito, and R. Mendoza (2007), MRO Ka-band demonstration: Cruise phase lessons learned, paper presented at IEEE Aerospace Conference, Inst. of Electr. and Electron. Eng., Big Sky, Mont.

Smith, D. E., M. T. Zuber, and G. A. Neumann (2001), Seasonal variations of snow depth on Mars, *Science*, *294*, 2141–2146.

Space Studies Board (SSB) (1996), *Review of NASA's Planned Mars Program*, Natl. Res. Counc., Washington, D. C.

SSB (2003), *New Frontiers in the Solar System: An Integrated Exploration Strategy*, 232 pp., Natl. Acad. Press, Washington, D. C.

Zuber, M. T., F. G. Lemoine, D. E. Smith, A. S. Konopliv, S. E. Smrekar, and S. W. Asmar (2007), Mars Reconnaissance Orbiter Radio Science Gravity Investigation, *J. Geophys. Res.*, doi:10.1029/2006JE002833, in press.

Zurek, R. (Ed.) (2001), Report of the NASA Science Definition Team for the Mars Reconnaissance Orbiter (MRO), Sci. Definition Team, NASA, Washington, D. C., 9 Feb.

Zurek, R. W., and L. J. Martin (1993), Interannual variability of planet-encircling dust storms on Mars, *J. Geophys. Res.*, *98*, 3247–3259.

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