# The Mars Reconnaissance Orbiter Mission
# IAC-05-A.3.3

James E. Graf, Richard W. Zurek, Howard J. Eisen, Benhan Jai, M.D. Johnston
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California, USA
jegraf@jpl.nasa.gov
Dr. Ramon Depaula
NASA HQ, Directorate of Mission and Science

## ABSTRACT

The Mars Reconnaissance Orbiter (MRO) was launched on August 12, 2005 by an Atlas V 401 expendable launch vehicle from Cape Canaveral Air Force Station, Florida, USA. The spacecraft supports a payload to conduct remote sensing science observations, identify and characterize sites for future landers, and provide critical telecom/navigation relay capability for follow-on missions. The mission is designed to provide global, regional survey, and targeted observations from a low 255km by 320km Mars orbit with a 3:00 P.M. local mean solar time (ascending node). During the one Martian year (687 Earth days) primary science phase, the orbiter will acquire visual and near-infrared high-resolution images of the planet's surface, monitor atmospheric weather and climate, and search the upper crust for evidence of water. While in this science phase, the orbiter will provide telecommunications support for Phoenix spacecraft launched to Mars in the 2007. After the primary science phase is complete, the orbiter will enter into its formal relay mode and support the Mars Science Laboratory which will be launched in the 2009 opportunity. The primary mission ends on December 31, 2010, approximately 5.5 years after launch

## 1. INTRODUCTION

The scientific objectives established by NASA's (National Aeronautics and Space Administration), Mars Exploration Program (MEP), has four major themes linked by a common strategy. The themes are:

- Search for evidence of past or present life;
- Understand the climate and volatile history of Mars;
- Understand the geology and geophysics of the Martian surface and subsurface; and
- Assess the nature and inventory of resources on Mars in anticipation of human exploration.

The strategy that links these themes is the search for water. Water is key to the origin, development, and sustenance of life as we know it on Earth. It is a crucial aspect of the planet's climate and a major agent in the modification of its surface over geologic time. Water is a resource that can be exploited in the future when humans go to Mars.

In June and July 2003, NASA launched two Landers (Mars Exploration Rovers – MER) to Mars. These landers have provided unprecedented in situ measurements of surface properties; however, these measurements cover relatively small geographic areas on the Martian surface. To expand the critical measurement suite and extrapolate ground truth measurements from landing sites to the entire planet, the MRO mission is planned for launch in 2005. Figure 1 shows an artist's rendition of the MRO spacecraft.

Figure 1. MRO Spacecraft

Imaging the surface at a ground sampling scale five times better than any prior mission, MRO will dramatically expand our understanding of Mars. The baseline science payload for the mission consists of a high-resolution imager (capable of resolving 1-meter-scale objects from 300km altitude), a visible/near infrared imaging spectrometer, an atmospheric sounder, a subsurface radar sounder, and a context optical imager. The engineering payload consists of the telecommunications package that will provide a proximity link to the surface and approach navigation support, and an optical navigation camera that will demonstrate precision entry navigation capability for future landers.

In addition to conducting detailed global and local science investigations, the payload suite will characterize sites for future landers. In this role, the observations from the payload suite perform double duty. They will both detect potentially hazardous terrain and obstacles in candidate landing sites as well as identify interesting mineral and geological formations that are attractive targets for a lander to visit.

The MRO mission has completed its development phase by conducting a successfully launch on August 12, 2005. It is presently in its 7-month cruise phase to Mars. Previous papers described the development phases of the mission [1,2] while another paper addresses in detail the mission operations and ground system design [3]; this paper provides the current status of MRO, including a summary of the launch activities, a detailed description of the cruise phase, and a brief summary of the remaining mission phases.

## 2. Mission Objectives

The driving theme of the Mars Exploration Program is to understand the role of water on Mars and its implications for possible past or current biological activity. The MRO Project will pursue this "Follow-the-Water" strategy by conducting remote sensing observations that return sets of globally distributed data that will: 1) advance our understanding of the current Mars climate, the processes that have formed and modified the surface of the planet, and the extent to which water has played a role in surface processes; 2) identify sites of possible aqueous activity indicating environments that may have been or are conducive to biological activity; and 3) thus identify and characterize sites for future landed missions.

The Mars Reconnaissance Orbiter (MRO) mission has the primary objective of placing a science orbiter into Mars orbit to perform remote sensing investigations that will characterize the surface, subsurface and atmosphere of the planet and will identify potential landing sites for future missions. The MRO payload will conduct observations in many parts of the electromagnetic spectrum, including ultraviolet and visible imaging, visible to near-infrared imaging spectrometry, thermal infrared atmospheric sounding, and radar subsurface profiling, at spatial resolutions substantially better than any preceding Mars orbiter. In pursuit of its science objectives, the MRO mission will:

- Characterize Mars's seasonal cycles and diurnal variations of water, dust, and carbon dioxide.
- Characterize Mars's global atmospheric structure, transport and surface changes.
- Search sites for evidence of aqueous and/or hydrothermal activity.
- Observe and characterize the detailed stratigraphy, geologic structure, and composition of Mars surface features.
- Probe the near-surface Martian crust to detect subsurface structure, including layering and potential reservoirs of water and/or water ice.
- Characterize the Martian gravity field in greater detail relative to previous Mars missions to improve knowledge of the Martian crust, lithosphere, and potentially atmospheric mass variation.
- Identify and characterize numerous globally distributed landing sites with a high potential for scientific discovery by future missions.

In addition, the MRO will provide critical telecommunications relay capability for follow-on missions and will conduct, on a non-interference basis with the primary mission science, telecom and navigation demonstrations in support of future MEP activities. Specifically, the MRO mission will:

- Provide navigation and data relay support services to future MEP missions.
- Demonstrate Optical Navigation techniques for high precision delivery of future landed missions.
- Perform an operational demonstration of high data rate Ka-band telecommunications and navigation services

Science Investigations and Instruments

To fulfill the mission science objectives, seven scientific investigations teams have been selected by NASA. Four teams (MARCI, MCS, HiRISE, and CRISM) are led by Principal Investigators (PI). Each PI lead team is responsible for the provision and operation of a scientific instrument and the analysis of its data. The PI lead investigations are:

- Mars Color Imager (MARCI)
- Mars Climate Sounder, (MCS)
- High Resolution Imaging Science Experiment, (HiRISE)
- Compact Reconnaissance Imaging Spectrometer for Mars, (CRISM)

In addition to the PI lead teams, there are two investigation teams that will make use of facility instruments. The facility instruments are:

- Context Imager, (CTX)
- Shallow (Subsurface) Radar, (SHARAD)

The MARCI PI and Science Team will also act as Team Leader (TL) and Team Members for the CTX facility instrument. The Italian Space Agency (ASI) will provide a second facility instrument, SHARAD, for flight on MRO. ASI and NASA have both selected members of the SHARAD investigation team with ASI appointing the Team Leader and NASA appointing the Deputy Team Leader.

In addition to the instrument investigations, Gravity Science and Atmospheric Structure Facility Investigation Teams will use data from the spacecraft telecommunications and accelerometers, respectively, to conduct scientific investigations.

*High Resolution Imaging Science Experiment (HiRISE).* The High Resolution Imaging Science Experiment (HiRISE) is capable of unprecedented image quality, resolution and coverage, relative to previous Mars missions. The instrument was provided by the University of Arizona. Dr. Alfred S. McEwen is the PI. The instrument aperture is 50cm and capable of a ground scale factor of 30cm/pixel at 300km altitude. The camera features a 1.15-degree FOV, which corresponds to a swath width of 6 km from 300km. Images may be taken in various data modes and can require anywhere between 0.5 to 28 gigabits.

Table 1. Science Investigation Objectives

| Instrument | Type | Measurement Objectives | Science Goals | Attributes |
|---|---|---|---|---|
| **CRISM** | High-Resolution Imaging Spectrometer | Hyper-spectral Image Cubes<br>514 spectral bands,<br>0.4-4 microns, 7 nm res.<br>*From 300km:*<br>20 m/pixel, 11 km swath | Regional & Local Surface Composition & Morphology | Key: Moderately High Spectral & Spatial Resolution,<br>Targeted & Regional Survey,<br>Very High Data Rate |
| **CTX** | Mono-chromatic Context Camera | Panchromatic (minus blue) Images<br>*From 300km altitude:*<br>30km swath & 6m/pixel<br>*Context Imaging for HiRISE/CRISM & MRO Science* | Regional Stratigraphy & Morphology | Key: Moderately High Resolution with Coverage,<br>Targeted & Regional Survey,<br>High Data Rate |
| **HiRISE** | High Resolution Camera (0.5 m aperture) | Color Images, Stereo by Site Revisit<br>*From 300km:* < 1 m/pixel<br>(Ground sampling @ 0.3 m/pixel)<br>*Swath*: 6km in RED (broadband)<br>1.2km in Blue-Green & NIR | Stratigraphy, Geologic Processes & Morphology | Key: Very High Resolution<br>Targeted Imaging,<br>Very High Data Rate |
| **MARCI** | Wide-Angle Color Imager | Coverage of Atmospheric clouds, hazes & ozone and surface albedo in 7 color bands (0.28-0.8 μm)<br>(2 UV, 5 Visible) | Global Weather & Surface Change | Key: Daily Global Coverage<br>Daily Global Mapping, Continuous Ops<br>Dayside, Moderate Data Rate |
| **MCS** | Atmospheric Sounder | Atmospheric Profiles of Water, Dust, CO2 & Temperature,<br>Polar Radiation Balance<br>0-80km vertical coverage<br>(Vertical Resolution ~ 5km) | Atmospheric Structure, Transport & Polar Processes | Key: Global Limb Sounding<br>Daily, Global Limb & On-Planet Mapping,<br>Cont. Ops. Day/Night<br>Low-Data Rate |
| **SHARAD** | Shallow Subsurface RADAR | Ground Penetrating RADAR<br>Transmit Split Band at 20MHz<br>< 1km; 10-20 m Vert. Resoln<br>1km x 5km | Regional Near-Surface Ground Structure | Key: Shallow Sounding,<br>Regional Profiling,<br>High Data Rate |
| **CRISM**: PI, *Scott Murchie*, Johns Hopkins Univ Applied Physics Lab<br>**CTX**: TL, *Michael Malin*, Malin Space Science Systems<br>**HiRISE**: PI, Alfred McEwen, University of Arizona | | | **MARCI**: PI, *Michael Malin*, Malin Space Science Sys<br>**MCS**: PI, *Daniel J. McCleese*, Jet Propulsion Lab<br>**SHARAD**: TL, *Roberto Seu*, Univ of Rome; DTL *Roger Phillips*, Wash Univ | |

*Compact Reconnaissance Imaging Spectrometer for Mars (CRISM).* The Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) will provide high-resolution hyperspectral images of areas on Mars in wavelengths from 0.4 to 4.0 micrometers (visible to short-wave infrared) for identifying key mineralogical indicators of water and hydrothermal systems at spatial scales smaller than a football field. Such data will be vital for targeting future landed missions. CRISM is being provided by the Johns Hopkins University Applied Physics Laboratory. Dr. Scott Murchie is the PI. CRISM features a single Ritchey-Chretien telescope with two spectrometers. The telescope has a 10cm aperture with a 2.06-degree field-of-view. The entire instrument is mounted on a gimbal, which allows it to follow a specific target on the surface as the orbiter flies overhead. The gimbal can scan a range of ±60 degrees in the along-track direction.

*Mars Climate Sounder (MCS).* The Mars Climate Sounder (MCS) is a reflight of an investigation flown on Mars Climate Orbiter (MCO). The purpose of this instrument is to explore the structure and aspects of the circulation of the atmosphere. This includes mapping the thermal structure of the atmosphere from the surface to an altitude of 80km, with a vertical resolution of 5km and mapping the seasonal and spatial variability of atmospheric pressure. The PI is Dr. Daniel J. McCleese from JPL. MCS consists of two identical, 4cm aperture telescopes mounted on an articulating pedestal. This instrument does not require pointing by the spacecraft. The articulation allows the instrument to view the surface of Mars, the limb of Mars, space, and calibration targets, while maintaining the orientation of the orbiter. MCS has extremely low data rates and will be operated continuously over the duration of the mission.

*Mars Color Imager (MARCI).* The Mars Color Imager, MARCI is another instrument selected as part of the reflight of the MCO investigations. The PI is Dr. Michael Malin from Malin Space Science Systems (MSSS). MARCI will take low spatial resolution observations of the atmosphere, providing daily global views of Martian activity, and examine surface features characteristic of the evolution of the Martian climate over time. This instrument is nadir-pointed and has a FOV of 180 degrees, which allows it to see limb-to-limb. MARCI has a selectable resolution between 1 and 10km per pixel using one of its five visible bands. Resolution using one of its two UV bands provides a resolution of better than 10km/pixel.

*Context Camera (CTX).* MSSS is providing the Context Camera (CTX) as a facility instrument, which will provide panchromatic context imaging for the targeted investigations and which will independently address the MRO science goals. In its support role, CTX typically will be operated simultaneously with the higher-resolution instruments. The team leader for this investigation is Dr. Michael Malin from MSSS. This instrument has a 5.8-degree field-of-view through its 10.8cm aperture, which is capable of a ground sample distance of 6m/pixel from an altitude of 300km. The 5000-pixel detector produces a swath width of 30km.

*Shallow Radar (SHARAD).* The Shallow Radar (SHARAD) will be used to the search for ground ice or water and sub-surface structure. SHARAD is being provided by the Italian Space Agency (ASI). This instrument is a nadir looking radar sounder with downtrack synthetic aperture capabilities. SHARAD operates at the 15-25 MHz frequency bands, and has a vertical resolution of approximately 15 meters. SHARAD is capable of probing as deep as 1km below the surface, but typically will profile structures closer to the surface. SHARAD will be operated primarily at night over selected targets, with an occasional polar observation across the terminator to 60 degrees latitude. SHARAD is located on the aft deck of the orbiter and will be deployed once the orbiter is in the primary science orbit.

*Facility Investigations.* In addition to the science instruments, there are two science investigations that rely on spacecraft subsystems to provide data. Dr. Maria T. Zuber is the TL for the Gravity Science investigation. By tracking the orbiter in the primary science phase, investigators will be able to better map the gravity field. Investigations on the structure of the atmosphere will be conducted using the data collected from the accelerometers during aerobraking. A facility investigation team led by Dr. Gerald Keating will conduct this analysis.

These MRO scientific observations will be carried out for one Mars year or more in order to characterize the full seasonal variation of the Martian climate and to target hundreds of globally distributed sites with high potential for further scientific discovery. The individual science instrument capabilities that must be met to achieve mission success are summarized in Table 1.

Engineering Payloads

To fulfill mission objectives of the MEP, MRO will carry the following engineering payloads and equipment:

- Electra, UHF communications and navigation package
- Optical Navigation (Camera)
- Ka Band Telecommunication Equipment

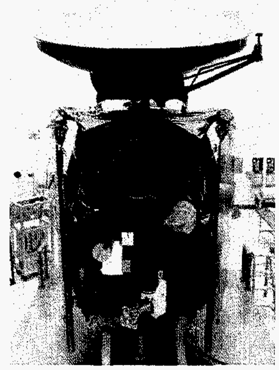

Figure 2. Final check-out for MRO Spacecraft at launch site

*Electra.* Electra is a UHF telecommunications package that will be used to provide a command and telemetry, or proximity link as well as collecting Doppler data for navigation to the surface and support Mars approach navigation. Electra will provide near omni-directional coverage of surface assets via its UHF antenna. It will also contribute navigational-related data in the form of one-way Doppler measurements through its Ultra Stable Oscillator (USO) and two-way Doppler measurements through the use of a transponder on other spacecraft or landed asset. It can also provide one- and two-way ranging measurements.

*Optical Navigation Camera.* The Optical Navigation camera carried on board the MRO is part of a technology demonstration experiment. The camera will acquire images of Mars and its moons, Phobos and Deimos. On future missions, it could yield more precise entry for Mars landers. The camera is located on the aft deck of the orbiter and will be pointed in the direction of Mars during approach. This allows the orbiter to acquire the appropriate Optical Navigation frames, while minimizing the amount of slewing required by the orbiter. This camera has an aperture of 6 cm, and a 1.4-degree square field-of-view. The spacecraft will command shutter times and exposure durations via sequences that are generated on the ground.

*Ka Band Telecommunications Demonstration.* The Ka-band equipment carried onboard MRO will permit an operational demonstration of high rate science data return from a low altitude orbit at mars. The Ka-band will be used in the same operational downlink modes as the primary X-band link, permitting a direct comparison of the two systems.

## 3. LAUNCH PHASE DESCRIPTION

The MRO spacecraft is the most capable spacecraft ever sent to Mars. (See Table 2 for a summary of the characteristics of the Mars Orbiter.) Figure 2 shows the spacecraft in final assembly at the launch site. Figure 3 shows the Atlas V 401 lifted off from SLC 41 at Cape Canaveral Air Force Station, Florida on Aug 12, 2005 at 11:43:00 GMT. The total MRO injected mass on the Atlas V 401 was 2180 kg. The dry mass was 981 kg; the rest of the injected mass was fuel. The launch targets were a C3 of 16.35 m2/s2, DLA of 39.47 degrees, and a RLA of 28.86 degrees. Spacecraft interleave telemetry was seen throughout all phases of the Atlas flight. The first stage booster was depleted and jettisoned 4 minutes into flight. The ground track took the craft south over the Atlantic Ocean where the second stage completed its first 9-minute burn. After an approximate 33-minute cruise, the second stage fired for a final time for approximately 6-minutes in duration. The spacecraft separated over Indonesia at approximately 12:40:52 GMT and successfully entered safe mode and started transmitting. The JAXA tracking station at Uchinora acquired frame lock approximately 2 minutes after separation and successfully flowed real time data to the three control centers located at JPL in Pasadena, at LMA in Denver, and back to the launch site. Post launch reconstruction indicated that the spacecraft tip-off rates were well within the 1 deg/sec requirement with a maximum about the x-axis of 0.3 deg/sec. After the spacecraft had entered safe mode, it successfully deployed all appendages in preparation for attitude acquisition. Post launch reconstruction confirmed that both solar arrays were fully deployed and latched. The deployment and articulation of the HGA was also smooth and successful. The design is such that there are no more deployments required of the engineering subsystems for the duration of the mission and only two payload deployments are required after achieving the final science orbit: the cover on the CRISM instrument and the 10 m antenna for the SHARAD instrument. Attitude was acquired on the first attempt and the star tracker began tracking between 8 and 9 stars. After acquiring inertial reference, the spacecraft successfully slewed to the initial acquisition attitude and transitioned to a healthy complement of reaction wheels. The lowest battery state of charge (SOC) seen throughout this activity was 99%. Goldstone acquired the MRO spacecraft at approximately 13:04:52 where full uplink commandability and two-way tracking was established.

After reconfiguring the uplink/downlink architecture for higher rate data and several post-launch clean-up activities, the spacecraft was commanded out of Safe Mode on 13 Aug in preparation for the L+3 day MARCI calibration. On 15 Aug the spacecraft was commanded to a sun-pointed attitude just prior to the calibration. The spacecraft powered-on the MARCI instrument and performed a series of slews to scan MARCI across the Earth to acquire the first science image from MRO. Data from the instrument was acquired and routed through the Solid State Recorder prior to downlink. This data enabled MARCI investigators to compare the UV measurements at Earth with those to be taken at Mars.

Table 2. Mars Orbiter Characteristics

| **Orbiter Characteristics** | |
|---|---|
| Mass – 2180 | Power – 6kW (BOL@Earth) |
| Solar Array Area – 20.5 $m^2$ (19 $m^2$ populated) | |
| Antenna Diameter – 3m | |
| Data Storage – 160 Gb | CPR Speed – 48 MIPs |
| 6 Science Instruments, 3 Engineering Payloads | |

Minor adjustments were needed for temperature set points in the Optical Navigation Camera and in the propulsion subsystem. A desaturation burn was performed to enable the reaction wheels to spin at slightly higher speeds to reduce wear. The battery state of charge remains around 115% with a bus voltage of 32.5V. The downlink rate off of the low gain antenna is 32 kb/s and the processor utilization remains a low 18%.

The first trajectory change maneuver (TCM) was executed successfully on the MRO spacecraft on August 27. Magnitude was 7.794 m/s, and included radial, tangential, and out of plane components which moved the spacecraft in toward the Sun, downtrack and up relative to the ecliptic, respectively, compared to the pre-TCM trajectory. The burn used six large 170 N MR-107N thrusters and six 22 N MR-106E thrusters. Approximately 1 m/s of the burn corrected the <1 sigma injection error from launch. The remainder removed the planetary protection bias in the injection targets and the additional bias introduced to permit use of the 170 N main engines at TCM-1. Burn time was 44.5 sec (30 sec settling burn; 14.5 sec main burn). The activity included articulation of the HGA, and a significant slew to the burn attitude. This TCM provided the in-flight verification of Mars Orbit Insertion modes of propulsion and attitude control subsystems. The burn attitude also required use of the rear-facing low gain antenna (LGA2). Estimates show a slight (<1%) overburn, well within accuracy requirements in both cross track and magnitude. The burn consumed approximately 7.6 kg of hydrazine and decreased propellant tank pressure by 12 psi. Solar arrays reached a maximum of 60 deg off sun, which still provided approximately twice the required power; therefore no energy was required from the batteries. LGA2 links agreed well with predicts. The activity was observed in real time with 2kb/s downlink.

The turn-on and initial check out of the instruments was performed from August 30 through September 2, 2005. The instruments were powered sequentially and all instruments turned on and returned instrument housekeeping data. Most objectives were achieved, although both the HiRISE and CRISM instruments terminated activities early due to internal temperature checks indicating anomalous conditions.

HiRISE turned on and acquired approximately two minutes of data before safing itself due to high temperature readings on the external support structure. The set points were adjusted and on September 2, HiRISE turned on and took its first images of deep space. CRISM finished an eight-step program that tested instrument articulation and checked out the instrument cooling system. Each of 3 instrument coolers were run for 20 sec and one was run for several hours, achieving within 10K of the IR detector target temperature (110K). At that point the instrument believed the IR detector had gotten too cold and safed itself. Investigation by the CRISM team indicated that the early turn-off was due to an error in a calibration curve that artificially lowered the detector temperature. The remaining test of the IR detector will be conducted in December.

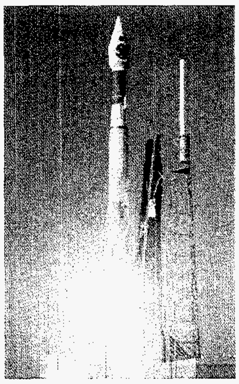

Figure 3. MRO Launch on August 12, 2005

## 4. DETAILED CRUISE PHASE DESCRIPTION

The MRO Mission has been divided into six major phases: Launch, Cruise, Approach and Orbit Insertion, Aerobraking, Primary Science, and Relay. Each phase name characterizes the principal activity that is occurring during that time period in the mission. Designed to communicate with the Deep Space Network (DSN) via a direct X-Band link, a majority of the mission will be conducted using the 34m antennas at two tracks per day. During MOI, supplemental coverage from the 70m antennas will be planned. Supplemental 70m antenna coverage is also being planned for the primary science phase. This paper will describe in detail the cruise phase and will briefly describe each phase of the other MRO mission phases.

Cruise lasts for about three-quarters of the entire Earth-Mars interplanetary trajectory, spanning about five of the seven months between Launch and Mars Orbit Insertion (MOI). Principal activity during the Cruise Phase includes daily monitoring of orbiter subsystems, navigation activities to determine and correct the vehicle's flight path to Mars as well as spacecraft subsystem and science payload checkout and calibrations. Two months before MOI, operations shift from Cruise to Approach Phase.

### Trajectory Characteristics

MRO uses a Type-I ballistic cruise trajectory for transfer between Earth and Mars, meaning that the spacecraft will travel less than a 180° central angle. No major deep space maneuvers are required post-launch. The cruise trajectory is designed to deliver the orbiter to Mars on a southern approach trajectory. Figure 5 shows top and edge-on views of the interplanetary trajectory including Cruise and Approach Phases.

In addition to monitoring health and status telemetry, Cruise activities include spacecraft subsystem checkouts and calibrations, payload checkouts and calibrations, and trajectory correction maneuvers (TCMs). An overview timeline showing the cruise activities is shown in Figure 6.

For the first fifteen days after launch the spacecraft telemetry from the various subsystems were closely monitored to characterize spacecraft performance. Tracking data was also collected to help navigation determine the flight path. Several days of tracking data were used to determine the details of the TCM-1 burn.

Transition to HGA activities occurred on September 20th, 41 days after launch. The Cruise Phase began with the HGA gimbals fixed near the initial acquisition position and used the LGA to downlink telemetry at 32kbs. This link was maintained for the first three weeks. For the rest of Cruise, the spacecraft will use a rate of 500 kbs over the HGA. During the switch to the HGA antenna, the first Ka-band pass was performed.
During the Cruise Phase, several spacecraft calibrations are performed to calibrate and determine the performance of various spacecraft subsystems relative to models or predicts. A complete listing of spacecraft calibrations is shown in Table 3 and they are described below.

### HGA Boresight/Gimbal Calibration/KaBand Check-out

For the HGA Boresight Calibration was performed on Sept. 9th. The spacecraft articulated the HGA through small ranges of motion and monitor the signal strength. Two spacecraft attitudes were used to monitor the signal strength over the HGA. This calibration confirmed that the electrical boresight of the antenna did not shift during launch and to partially determined any outer gimbal misalignments. Both X and Ka boresights were successfully checked out individually and relative to one another. Additional telecom subsystem calibrations are planned to support the Ka-band experiment. These events will occur over approximately 10 DSN passes, using Ka-band-capable stations. The first Ka-pass coincided with the transition to HGA activities. These calibrations will be used to verify the end-to-end functionality and performance of the Ka-band link, testing various data rates, coding schemes, and station options.

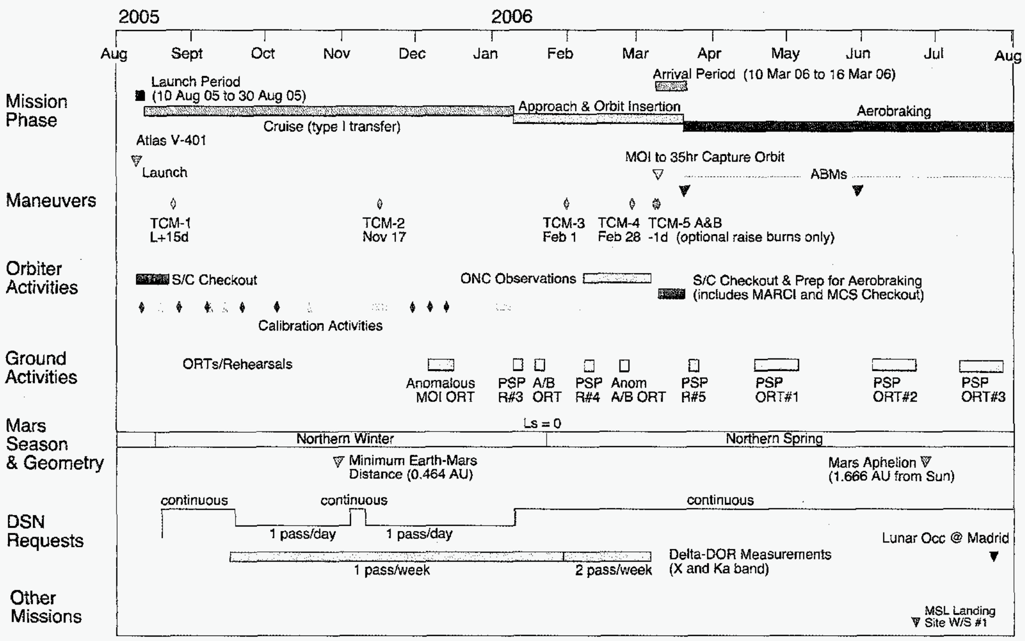


Figure 5. Cruise Phase timeline

ACS Thruster Calibration

The ACS Thruster Calibration measured the trajectory perturbations caused by Angular Momentum wheel Desaturations (AMDs). Angular Momentum Desaturations are performed by spinning down the reaction wheels, while the ACS thrusters provide opposing torques. Since the coupled thrusters are not perfect, a small but unknown translational delta-V will be imparted to the spacecraft by each AMD event. To measure the error in the couple, AMDs were performed both increasing and decreasing the wheel speed, about each primary axis, from three different spacecraft attitudes (18 total burn activities). The activity began with an AMD to set the wheel speed at the desired initial speed for the calibration. The spacecraft was continuously tracked by the DSN over the LGA to collect Doppler data to measure the residual delta-V.

HiRISE to Star Tracker Alignment Calibration

The HiRISE to Star Tracker Alignment Calibration will determine the relative alignment of HiRISE and the star tracker focal planes, including both boresight and twist components. This will be used to establish the error in the spacecraft inertial pointing accuracy for the HiRISE camera, as well as to support the targeting needs during Cruise and Primary Science Phases. The activity involves three large HiRISE images of the M11 star cluster, which also provides the second HiRISE focus adjustment. For this and every other HiRISE cruise calibration image, 200 Hz IMU data and 5 Hz Star Tracker star vectors will be measured to support HiRISE pointing needs.

Table 3: Spacecraft Subsystem Activities on First Day of Launch Period

| Calibration Activity | Time Frame | Subsystem | Objectives |
|---|---|---|---|
| HGA Boresight and Gimbal Calibration | Sept 9 (L+30) | Telecom | Necessary for high data rates |
| Thruster Calibration | Sept 15 (L+36) | GNC | Determine the translational delta-v imparted by thrusters during AMDs |
| Switch to HGA and Ka-band pass 1 of 10 | Sept 20 (L+41) | Telecom | Test Ka-band link |
| HiRISE to Star Tracker Alignment | Oct 5-6 (L+56-57) | HiRISE, GNC | Determine the inertial pointing accuracy |
| Gyro to Star Tracker Alignment | Oct 19 (L+70) | GNC | Needed to support precision targeting Verify inertial pointing |
| SRP and Gravity-2 Calibrations | Dec 29-Jan 5 (L+141 -148) | GNC | Measure the torque as a result of SRP, and its impact on NAV |

Gyro to Star Tracker Alignment

The Gyro to Star Tracker Alignment calibration uses one positive and one negative turn about each of the spacecraft body axes to relate the axes of the inertial measurement units and star trackers for verification of spacecraft inertial pointing accuracy, which is used to support targeting in the Cruise and Primary Science Phases. The objectives of this calibration are to determine in-flight alignment of gyro axes to the Star Tracker reference and to determine the gyro rate bias.

Solar Radiation Pressure (PRP) Calibration

The final navigation-related activity in Cruise is the Solar Radiation Pressure (SRP) Calibration. For a period of eight days near the end of the Cruise Phase, the spacecraft activities will be minimized so that small forces on the spacecraft from solar radiation pressure can be measured. The spacecraft will assume two different attitudes with the HGA boresight pointed at Earth—the normal Cruise attitude and an off-pointed attitude. Each attitude will be held for four days and tracking information will be used to characterize the surface properties of the major spacecraft components.

Instrumental Activities

In order to fully characterize instrument performance, in-flight calibrations of the payloads will need to be performed. Including the MARCI UV calibration, there are several payload activities that are planned during the Cruise Phase. Table 4 lists the approximate timeframe for these activities, as well as the participating instruments and their objectives.

These calibration activities achieve several different objectives. Radiometric calibrations measure the sensitivity of the instrument. Geometric calibrations measure the alignment of the detector focal plane, as well as the pointing of the instrument. Stray light calibrations seek to characterize any other sources of light entering the instrument. HiRISE images of a stellar target will be used to characterize jitter disturbances from other payloads. Additionally, the orbiter Electromagnetic Interference environment will be characterized by both SHARAD and Electra in receive-only ("sniff") mode.

During the payload check-out phase, the spacecraft is still on the Low Gain Antenna so data volume is constrained by the transmit capability of the 32 kbs data rate. The orbiter will collect health and status telemetry from the instruments and transmit it to the ground. Payload checkouts require minimal special interaction with the spacecraft and include:

- *Power on each payload*
- *Perform and report self-diagnosis*
- *Monitor power and thermal responses*
- *Check command, telemetry, and data interfaces*

In addition to power up and power down, instruments run through a basic functional test similar in most cases to ATLO checkouts but with modifications necessary to satisfy some fundamental need of the investigation that can not be met simply by repeating the off-the-shelf ATLO test.

Table 4. Payload Cruise Calibrations for the First Day of the Launch Period

| Calibration Activity | Time Frame | Instruments | Objectives |
|---|---|---|---|
| **MARCI UV** | Aug 13 (L+3) | MAR | Radiometric in the UV bands |
| **L+18 Instrument Checkout** | L+18,19 (Aug 28-29) | HIR, CTX, CRM, MAR, SHR, MCS, ONC, EUT | Verify payloads survived launch and operate as expected. SHARAD EMI test. Electra clock set. |
| **Lunar–OC and ONC-1 Calibrations** | Sept 7-8 (L+28-29) | HIR, CTX, ONC, IMUs and Star Trackers | HiRISE and CTX: stray light geometric, radiometric.<br>ONC: geometric |
| **MCS Solar Target Calibration** | Sept 12 (L+33) | MCS | Calibrate the MCS Solar Target |
| **Electra/Stanford Test** | Sept 21-22 (L+42-43) | EUT | Characterize antenna pattern with stable Earth source |
| **Gravity-1 Calibration** | Nov 14-20 (L+96-102) | DSN tracking in support of TCM-2 | Create baseline far from gravity fields |
| **ONC-2 Calibration** | Nov 30 (L+112) | ONC | Geometric |
| **Stellar-1 Calibration** | Dec 6-7 (L+118-119) | HIR, CTX, IMUs and Star Trackers | Geometric, Radiometric |
| **Stellar-2 Calibration** | Dec 13-14 (L+125-126) | HIR, CTX, SHR, MCS, CRM, EUT, MAR, IMUs and Star Trackers | Geometric, Jitter, EMI |
| **Gravity-2 Calibration** | Dec 29-Jan 5 (L+141-148) | Uses s/c tracking data | Create baseline far from gravity fields |

In order to accurately measure ozone abundances at Mars, the UV channels on the MARCI instrument need to be calibrated using the only extended UV objects available before arrival at Mars. Because of the very large field of view of MARCI, both the Earth and Moon can be viewed with a small slew from the standard cruise

The Lunar/Omega Centauri imaging is highly desired by the payloads for several reasons. First, the Moon is a unique target that has a very sharp limb due to the lack of an atmosphere and this allows for the evaluation of potential stray light problems. Next, the side of the Moon that faces the Earth is a very well characterized source for both visible and near-infrared light, thus allowing very accurate radiometric and geometric measurements.

ONC imaging occurs just before the first HiRISE scan and just after the last scan from the two different attitudes. The stellar target, Omega Centauri (OC), is used for the first of three HiRISE focus tests, as well as focal plane, boresight, and geometric alignment calibrations of HiRISE and CTX. The Optical Navigation Camera (ONC) will perform the first of two ONC exposure calibrations to test and verify the settings in coordination with the other instrument activities. The first HiRISE image of the moon is shown in Figure 7.

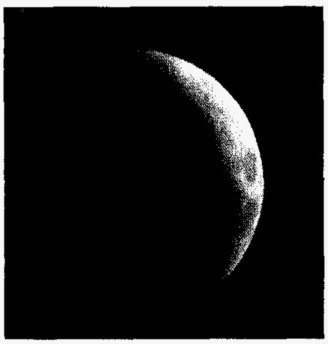

Figure 7. HiRISE image of Earth's moon taken at a distance of 6 million km

As with all Cruise activities, the participating instruments will be powered on and checked-out 24 hours prior to the lunar observation. For the Lunar-OC calibration, the orbiter will slew to point CTX and HiRISE at the appropriate attitude to scan the instrument fields-of-view across the Moon and the globular cluster Omega Centauri, simulating in-orbit motion. HiRISE and CTX will image both targets simultaneously in the forward scan direction. HiRISE will need three forward scans across the center portion of its field-of-view, with over three hours between images to cool the HiRISE electronics.

MCS Solar Target Calibrations

The MCS Solar Target, which is used to calibrate the visible channel, will darken with exposure to solar UV. This darkening needs to be measured during the Cruise portion of the mission. The first step is to measure the target before any significant darkening occurs to provide a point of comparison with pre-launch laboratory measurements. The standard cruise attitude places MCS in the shadow of HiRISE but the solar target does accumulate exposure during other activities like the Lunar Calibration. A second activity will be performed during the Stellar-2 timeframe.

Electra/Stanford UHF Test

The Electra/Stanford UHF Test between the orbiter's Electra payload and the Stanford UHF antenna will map the UHF antenna pattern and characterize performance at both standard Electra frequencies. Checkout activities prior to this calibration include a link verification test with Stanford at two operating frequencies 24 hours prior to the calibration at each of Electra's frequencies.

Electra's UHF pattern is designed to provide a 60 degree half-cone angle antenna pattern to communicate with assets on the surface of Mars. Objects mounted on the orbiter can interfere with the antenna pattern. To measure the pattern, Electra will transmit continuously to the Stanford ground station, carrier only, while the spacecraft maneuvers through several different profiles. Scan profiles are performed by pointing the nadir deck (+Z-axis) at 60, 40, and 20 degrees off-pointed from Earth while spinning a full circle about the spacecraft Z-axis. Each profile cone is performed at both Electra frequencies, swapping the frequency in the middle of the activity sequence. In addition to the cone profiles, Electra will perform peak power measurements with its boresight Earth-pointed.

Stellar Calibrations

The Stellar calibrations consist of two sets of observations, separated by one week. To ensure that the orbiter can accurately point to the desired target, the stellar calibrations will be performed after the HiRISE-Star Tracker alignment calibration. Once the orbiter is in the correct attitude for imaging, the spacecraft will slew the instruments back and forth several times across the targeted star field using different instrument settings. Up to four, 45-minute image sessions will be used, depending on the data volume required for each observation and the associated thermal limits of the instruments.

The stellar calibrations use the stars in the targeted clusters as point sources to set focus and exposure settings and determine geometric alignment (Stellar-1), and test the effect of jitter on HiRISE images and measure the EMI environment (Stellar-2).

The second Stellar Calibration (Stellar-2) will be used to determine the alignment of other instruments relative to HiRISE, including a second co-alignment measurement between CTX and HiRISE. Another important goal of this activity is to quantify the effect of jitter on HiRISE imaging from articulating MCS and CRISM gimbals and the CRISM cryo-coolers. All of the instruments, including Electra, are expected to participate in this series of observations in some manner, so that inter-instrument disturbances can be characterized. During this calibration, CRISM will perform an observation of its internal calibration target to measure the effectiveness of decontamination during Cruise.

Facility Investigations

In addition to the payload calibrations for the other investigations, the Project will also collect data for use by the facility investigations during Cruise. For the Atmospheric Facility team, high-rate Inertial Measurement Unit (IMU) and accelerometer data will be collected during the TCMs, in preparation for their data analysis during aerobraking.

The Gravity Science Team will be provided with radiometric tracking data collected from two separate timeframes, each with at least 72 hours of "quiet" spacecraft and constant DSN coverage. Tracking data collected from the three days before and after the second trajectory correction maneuver and during the eight-day long SRP will be available to the Gravity Science Team to satisfy this need. The objective is to characterize the end-to-end in flight Doppler error under quiet conditions, which ultimately dictates the quality of the gravity data.

## 5. SUMMARY OF REMAINING PHASES

Approach and Orbit Insertion

During the last sixty days of the interplanetary transit, spacecraft and ground activities will become focused on the events necessary for a successful arrival and safe capture at Mars. Navigation techniques will include the use of delta-DOR measurements in the orbit determination. This technique will yield a precise determination of the inbound trajectory with a series of final TCMs used to control the flight path of the spacecraft up to the MOI maneuver.

Also during the approach phase, MRO will perform the Optical Navigation experiment. This involves pointing the optical navigation camera (ONC) at the moons of Mars - Phobos and Deimos, and tracking their motion. By comparing the observed position of the moons to their predicted positions, relative to the background stars, the ground will be able to accurately determine the position of the orbiter.

Upon arrival at Mars on March 10, 2006, the spacecraft will perform its MOI maneuver using its six main engines. MOI will insert the spacecraft into an initial, highly elliptical capture orbit with a period of 35 hours. The DV required to accomplish this critical maneuver is 1015 m/s and will require approximately 25 minutes to complete. For most of the burn, the orbiter will be visible from the DSN stations. The signal will be occulted as the orbiter goes behind Mars. The orbiter will appear again a short time later. The reference MRO capture orbit has a period of 35 hours and a periapsis altitude of 300km. The orientation of the ascending node will be 8:30 PM LMST. The node of the capture orbit node has been selected such that aerobraking operations can be completed prior to the start of the solar conjunction blackout (September 23, 2006).

Aerobraking

One week after MOI, aerobraking operations will commence. During this time period, the orbiter will use aerobraking techniques to supplement its onboard propulsive capability and reduce its orbit period to that necessary for the primary science orbit (PSO). Aerobraking will consist of 4 distinct phases: a walk-in phase, a main phase, a walkout phase and a transition to the PSO. During the walk-in phase, the spacecraft establishes initial contact with the atmosphere as the periapsis altitude of the orbit is slowly lowered. This phase continues until the dynamic pressures and heating rate values required for main phase, or steady state aerobraking, are established. During main phase, large scale orbit period reduction occurs as the orbiter is guided to dynamic pressure limits. Main phase continues until the orbit lifetime of the orbiter reaches 2 days. (Orbit lifetime is defined as the time it takes the apoapsis altitude of the orbit to decay to an altitude of 300km.) When the orbit lifetime of the orbiter reaches 2 days, the aerobraking walkout phase will begin. During the walkout phase, the periapsis altitude of the orbit will be slowly increased as the 2 day orbit lifetime of the orbiter is maintained. Once the orbit of the orbiter reaches an apoapsis altitude of 450km, the orbiter will terminate aerobraking by propulsively raising the periapsis of its orbit out of the atmosphere.

Because the PSO has nodal orientation requirements, the aerobraking phase of the MRO mission must proceed in a timely manner and be completed near the time the desired nodal geometry is achieved. At the initial establishment of main phase, dynamic pressure limits will be set such that the orbiter will fly toward a 3:15 pm LMST nodal target. After approximately 4.5 months of aerobraking, the dynamic pressure control limits will be reset such that the orbiter will fly to the desired 3:00 pm LMST nodal target. The total duration of actual aerobraking activities is about 5.5 months. During this time, the spacecraft will perform approximately 560 orbits.

Once aerobraking has been terminated, MRO will perform a series of propulsive maneuvers to establish the primary science orbit. The transition time from aerobraking to the primary science orbit will take approximately 10 days.

Primary Science

The primary science orbit (PSO) has been designed to satisfy the science requirements of the mission. This orbit has the following characteristics:

- a Sun-synchronous ascending node at 3 P.M. local mean solar time (LMST) -- daylight equatorial crossing (near polar inclination of 92.7 deg);
- an eccentricity and argument of periapsis that results in a low altitude "frozen" orbit (periapsis altitude of 255km, apoapsis altitude of 320km, and an argument of periapsis of 270 deg); and
- a semi-major axis that will produce a 17-day (short term) groundtrack repeat cycle (semi-major axis of 3775km).

Because of the 3:00 pm LMST orbit orientation, the MRO spacecraft will experience a solar eclipse on each orbit. Additionally, on almost every orbit, the spacecraft will experience an Earth occultation. The Earth occultations cause the orbiter to lose contact with the DSN. This has a noticeable effect on the downlink data volume capability of the mission.

To simplify the complex observation geometry associated with other types of low altitude orbits at Mars, the MRO spacecraft will be put into a "frozen" orbit. The "frozen" orbit condition results in a periapsis that remains stationary over the South Pole of Mars. With the periapsis location fixed, a 65-70km range between the periapsis and apoapsis altitudes above the surface results naturally due to the Martian gravity field. Variations in the spacecraft altitude above the Martian surface at specific latitudes are limited to just a few kilometers. A plot of altitude versus latitude is shown in Figure 8. It should be noted that the periapsis of the MRO orbit is 115km lower than that of current spacecraft (Mars Global Surveyor and Mars Odyssey) orbiting at Mars.

Because of the different observations modes (global mapping and profiling, regional survey, and globally distributed targeting) of the science suite, the PSO has been designed to produce two groundtrack repeat cycles. First, there is a long-term repeat cycle that provides uniform, global coverage of Mars with a fine grid of less than 5km at the equator. Except for atmospheric perturbations, this is the exact repeat of the groundtrack that will occur after 4602 revs [359 days (349 sols)]. Second, there is a short-term repeat cycle, or targeting cycle, that will occur every 211 revs [17 days (16.5 sols)]. The targeting cycle is not an exact repeat; it has a 31 km westward walk relative to any selected reference node. This short term repeat cycle allows for quick global access to the planet and repeated targeting (data take) opportunities. Due principally to atmospheric perturbations, the planned groundtrack repeat cycles may not be easily achievable. Regular orbit trim maneuvers are expected to be necessary in order to control the groundtrack repeat patterns. Because of the potential groundtrack control issues and as a way to enhance the targeting aspect of the mission, the spacecraft has been designed to roll and take data ±30 degrees crosstrack of nadir. For the altitude range of the PSO this is equivalent to approximately 165km on the surface. Because of impacts to global mapping investigations, targeted observations with roll angles less than 10 degrees will be preferred.

Relay

Following the completion of the primary science objectives of the mission, the MRO orbiter will support the Mars exploration program by providing approach navigation and relay communications support to various Mars landers and orbiters through its telecommunications/navigation subsystem. Additionally, MRO has the ability to continue its scientific observations, including evaluation of future landing sites, for an additional Mars year as an asset for the Mars Program.

## 6. Summary

MRO is a flagship mission of the Mars Exploration Program. This mission will greatly enhance our understanding of Mars by returning new and high resolution scientific observations. The MRO spacecraft and its scientific payload reflect a state of the art design for planetary exploration. Over the course of its mission lifetime, MRO is expected to return more than 34 Terabits of data. The analysis of this data will undoubtedly shape the future of Mars exploration for many years to come.

## 7. References


[1] J. Graf , R. Zurek, R. Jones, H. Eisen, M. Johnston, B. Jai, R. De Paula, "An Overview of the Mars Reconnaissance Orbiter Mission", *2002 IEEE Aerospace Conference Proceedings,* March 11-15, 2002.

[2] J. Graf, R. Zurek, R. Jones, H. Eisen, M. Johnston, B. Jai, R. De Paula, "The Mars Reconnaissance Orbiter Mission", Acta Astronautica, 55th IAC, Vol. 57, Issue 2-8, 2005.

[3] B. Jai, C. Kloss, B. Hammer, D. Wenkert, M. Carlton, "The Mars Reconnaissance Orbiter Mission Operations: Architecture and Approach", *6th IAA International Conference on Low-Cost Planetary Missions,* October 2005.

[4] "Mars Reconnaissance Orbiter Mission Plan-Revision C", JPL D-22239, MRO 31-201, National Aeronautics and Space Administration, Jet Propulsion Laboratory, July 2005.


## 8. Acknowledgments


The authors want to thank Janis Capraro for her assistance in the preparation of this manuscript, and acknowledge the efforts and contribution of Robert Lock in the cruise section detail. The research described in this (publication or paper) was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.