The Mars Reconnaissance Orbiter Mission: From Launch to the Primary Science Orbit

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Richard Zurek
California Institute of Technology

Benhan Jai
National Aeronautics and Space Administration

The Mars Reconnaissance Orbiter Mission: From Launch to the Primary Science Orbit

M. D. (Dan) Johnston, James E. Graf, Richard W. Zurek, Howard J. Eisen, Benhan Jai, James K. Erickson
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California, USA

Martin.D.Johnston@jpl.nasa.gov

Abstract— The Mars Reconnaissance Orbiter (MRO) was launched from Cape Canaveral Air Force Station, Florida, USA, aboard an Atlas V-401 launch vehicle on August 12, 2005. The MRO spacecraft carries a very sophisticated scientific payload. Its primary science mission is to to provide global, regional survey, and targeted observations from a low altitude orbit for one Martian year (687 Earth days). After a seven month interplanetary transit, the spacecraft fired its six main engines and established a highly elliptical capture orbit at Mars. During the post-MOI early check-out period, four instruments acquired engineering-quality data. This was followed by five months of aerobraking operations. After aerobraking was terminated, a series of propulsive maneuvers were used to establish the desired low altitude science orbit. As the spacecraft is readied for its primary science mission, spacecraft and instrument checkout and deployment activities have continued. After the science phase is completed, the orbiter will provide telecommunications support for future Mars missions. This paper will provide a status of the actual mission to date (through October 2006) and briefly describe the planned operations for the upcoming science mission.

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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 was developed and launched in 2005. Figure 1 shows an artist's rendering of the MRO spacecraft.

Figure 1. Artist rendering of the 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.

[1] IEEEAC paper #1001, Version 6, Updated July 1, 2006

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.

Currently the MRO spacecraft is being readied for the commencement of science operations. After a 13 month journey, the spacecraft has successfully been delivered into its primary science orbit at Mars. Previous papers have described the initial formulation [1] and design phases of this mission [2], [3]. This paper provides a status of the actual mission to date (October 2006), spanning the time period from launch to the establishment of the science orbit at Mars. This status includes a summary of the mission objectives and a brief description of the spacecraft and its payloads.

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.

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

Table 1. Science Investigation Objectives

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

3. ORBITER DESCRIPTION

The MRO spacecraft is without question the state-of-the-art for planetary orbiters at Mars. Figure 2 shows the spacecraft in its orbital configuration. The vehicle consists of two major components: 1) the spacecraft bus and 2) the payload suite. The section describes the key attributes of the orbiter.

System Description

The allowable MRO injected mass on the Atlas V 401 launch vehicle was 2180 kg. The spacecraft dry mass at launch was 981 kg (versus an allocation of 1031 kg).. Because the spacecraft dry mass came in lighter than expected, the MRO propellant load was increased in order to give the spacecraft additional DV capability. This resulted in a total spacecraft DV capability at launch of 1680 m/s (versus a required capability of 1545 m/s). The total DV capability can be broken down into a required translational DV capability of 1395 m/s, a required rotational DV capability of 150 m/s, and a reserve capability of 135 m/s. The majority of the translational DV capability was used for capture at Mars.

To accomplish the needed targeted observations, the spacecraft is 3-axis stabilized with large momentum wheels providing stability and control. Additionally, the spacecraft has an impressive telecommunications and command and data handling architecture enabling large volumes of scientific data to be returned to Earth. Applying lessons learned from previous missions, solar array and high gain antenna deployments occur shortly after launch avoiding long term deep space exposure. The antennas are arranged such that there is a reliable communications path from every orbiter attitude. To ensure safe capture at Mars, the propulsion system is fault tolerant to a single main engine out and a short duration computer reset event. To avoid the hazards and risks of a bipropellant propulsion system, MRO utilizes a monopropellant hydrazine design. Designed to aerobrake, the spacecraft will quickly "right itself" (i.e. shuttlecock) in the event of a large attitude excursion when it enters the Martian atmosphere. The use of aerobraking reduces the total DV requirements of the mission by nearly 1200 m/s.

Spacecraft Bus

The major spacecraft subsystems include thermal, propulsion, telecommunications, command and data handling, electrical power, and guidance, navigation, and control. Descriptions of those subsystems can be found in Reference 4.

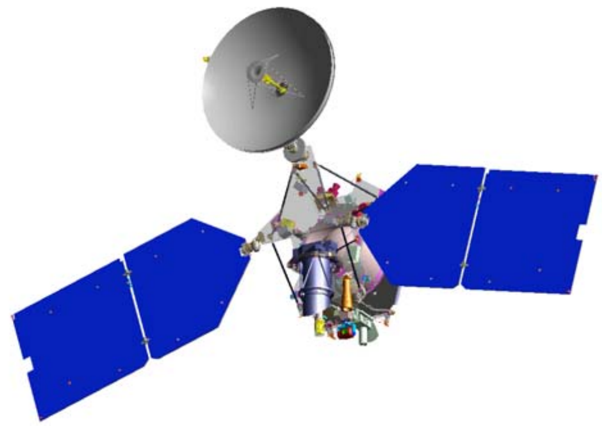

Figure 2. MRO spacecraft in its orbital configuration

Table 2. Orbiter Characteristics

Orbiter Characteristics
Mass – 2180 k
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

Payload

As discussed, in Section 2, the orbiter payload will consist of six science instruments and three engineering payloads. Figure 4 shows the layout of the principal science instruments.

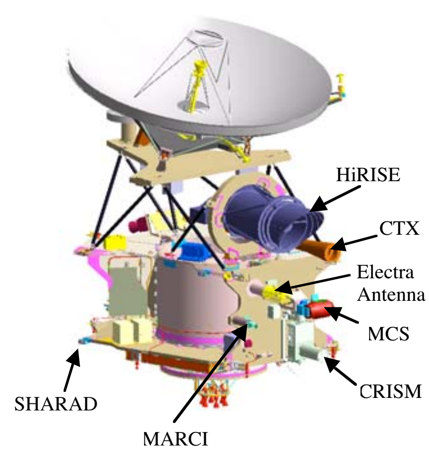

Figure 3. Layout of instruments on nadir deck

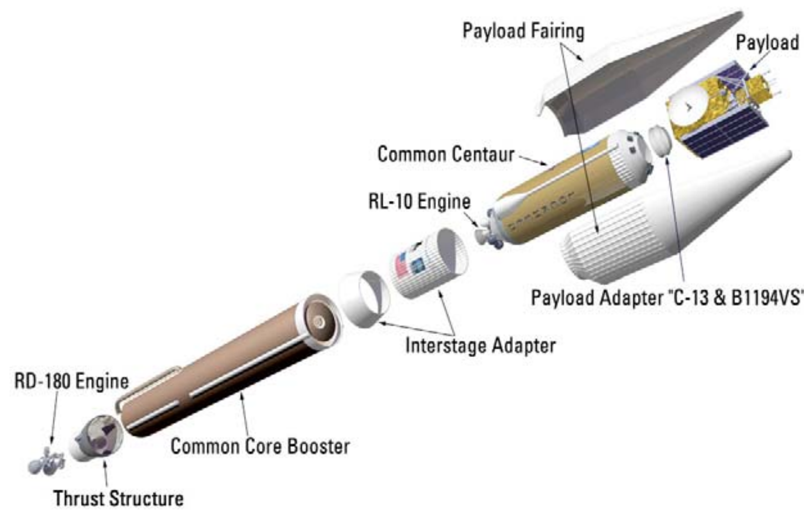

Figure 4. Atlas V401 launch vehicle

4. MISSION TO DATE (OCTOBER 2006)

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 was planned. This section will summarize the mission events and activities that have occurred since launch. It will cover the Launch, Cruise, Approach and Orbit Insertion, and Aerobraking mission phases.

Figure 5. Liftoff of the Atlas V401 with MRO

Launch Phase

The launch vehicle used for the MRO mission was the Lockheed-Martin Atlas V 401. The launch vehicle is shown in Figure 4. The MRO primary launch period was 21 days in length and extended from August 10 through August 30, 2005. Three contingency launch days were developed that spanned the time period from August 31 through September 2, 2005. Nearly every launch day had a two-hour daily window. Due to Atlas Booster considerations the first day of the launch period was not used. Because of poor weather conditions, the second day of the launch period was also scrubbed. On August 12, 2005, at 11:43: 00 UTC, the Atlas V 401 lifted off from SLC 41 at Cape Canaveral Air Force Station, Florida. Figure 5 shows the lift-off of the Atlas V 401 with MRO.

The Atlas launch vehicle departed SLC 41 on a flight azimuth of 93.5 deg. Per plan, 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 spacecraft south over the Atlantic Ocean where the second stage completed its first 9-minute burn. After an approximate 33-minute coast, the second stage fired for a second time achieving its interplanetary departure conditions: a C3 (injection energy) of 16.4 m2/s2, a DLA (declination of the launch asymptote) of 39.5 degrees, and a RLA (right ascension of the launch asymptote) of 28.9 degrees. The second burn of the Centaur lasted for approximately 6-minutes. Figure 6 shows an artist's rendition of the Centaur upper stage injecting the MRO spacecraft onto its interplanetary transfer trajectory. The spacecraft separated over Indonesia at approximately 12:40:52 UTC and successfully entered its planned 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 three control centers located at JPL in Pasadena, at LMA in Denver, and back to the launch site.

Figure 6. Artist rendering of the Centaur/MRO spacecraft injection

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 its planned safe mode, it successfully deployed all appendages in preparation for attitude acquisition. Analysis also confirmed that both solar arrays were fully deployed and latched. The deployment and articulation of the HGA was smooth and successful. No more deployments are required of the spacecraft 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 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 August 13. On August 15, the spacecraft was commanded to a sun-pointed attitude. Because the Earth is a unique calibration target, the spacecraft powered-on the MARCI instrument and performed a series of simple slews to scan the MARCI instrument across the Earth and Moon and acquired the instrument calibration data. Data from the instrument was acquired and routed through the Solid State Recorder prior to downlink. These data will enable MARCI investigators to compare the UV measurements at Earth with those to be taken at Mars.

The thermal performance of the spacecraft in its new space environment was nominal. Minor adjustments were needed for temperature set points in the Optical Navigation Camera and in the propulsion subsystem. The attitude control system maintained the spacecraft in a stable attitude. A desaturation burn was performed to enable the reaction wheels to spin at slightly higher speeds to reduce wear. The battery state of charge remained around 115% with a bus voltage of 32.5V. The downlink rate off of the low gain antenna was 32 kb/s and the spacecraft processor utilization was around 18%.

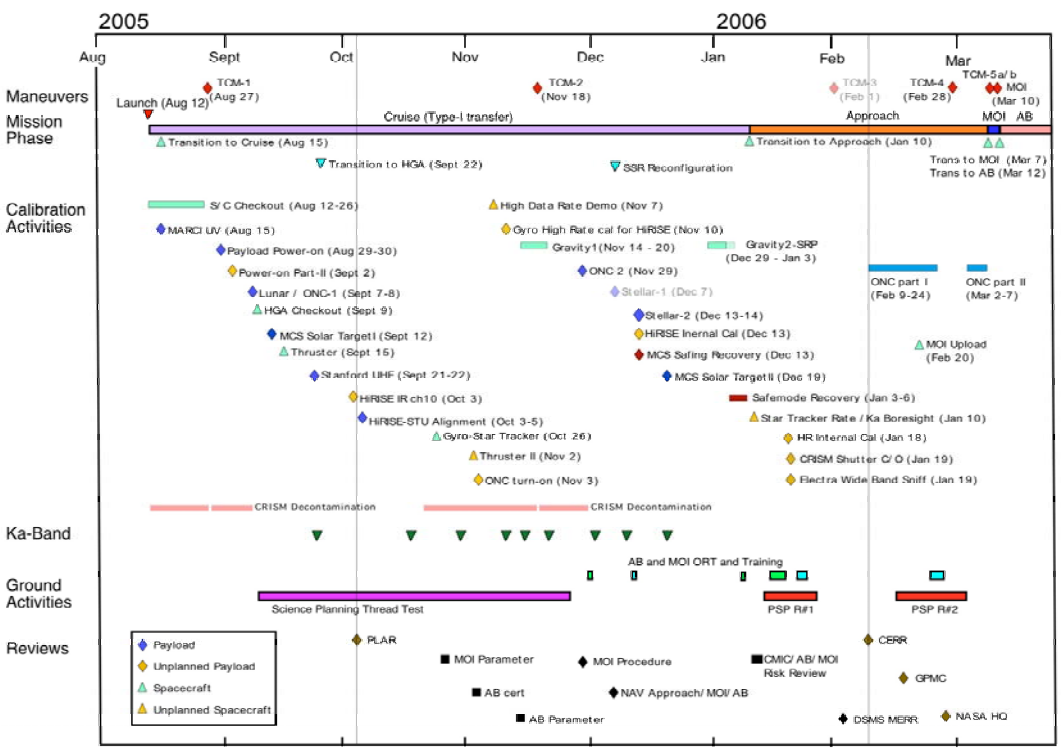

Figure 7 – Spacecraft and Payload Activities – As Flown

Cruise Phase

MRO used a Type-I ballistic cruise trajectory for transfer between Earth and Mars, meaning that the spacecraft will travel less than a 180° central angle and no major deep space maneuvers are required post-launch. The cruise trajectory was designed to deliver the orbiter to Mars on a southern approach trajectory. The total interplanetary transfer time was seven months. For a launch on August 12, 2005, Mars encounter and orbit insertion would occur on March 10, 2006.

The Cruise phase spanned the first 5 months of the interplanetary transit. Principal activities during the Cruise Phase included 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. The calibration activities can be broken down into two major groups – one group for spacecraft characterization and one group for payload characterization. The spacecraft calibrations consisted of antenna checkouts, thruster calibrations, solar pressure/torque measurements and gyro alignment calibrations. Payload calibrations included UV, stellar, and stray light calibrations as well as a characterization of the UHF performance of the Electra telecommunications package. Figure 7 shows the actual cruise phase activities performed by MRO. Twenty of these activities were part of the pre-launch mission plan. As the mission developed post-launch, an additional nine activities were performed. Some of the unplanned activities were either repeats or extensions of some of the planned activities or identified after launch to insure integrity and safety of the spacecraft and/or payloads.

Trajectory Correction Maneuvers

Four trajectory correction maneuvers (TCMs) were planned to control the interplanetary flight path. In addition, two emergency TCMs were planned to raise periapsis altitude just before the MOI maneuver in the event navigation solutions indicated an arrival altitude much lower than that desired. These two emergency TCMs were planned for execution at 24 hours (TCM-5A) and 6 hours (TCM-5B) before MOI. The TCM schedule is shown in Figure 7.

The first trajectory change maneuver (TCM-1) was executed successfully on the MRO spacecraft on August 27. 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. Magnitude of the TCM-1 burn was 7.79 m/s, and included radial, tangential, and out of plane components which moved the spacecraft slightly 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). The burn consumed approximately 7.6 kg of hydrazine. The 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 second trajectory correction maneuver (TCM-2) was executed on November 18. TCM-2 was designed to achieve the desired conditions for Mars approach taking into account the characteristics of the Mars Orbit Insertion (MOI) maneuver. TCM-2 targeted an approach altitude for periapsis of 491 km and an inclination of 93.4 deg. As with TCM-1, Navigation used several days of tracking data to design the TCM-2 burn. The magnitude of this maneuver was 0.75 m/s and it was performed using the six 22 N MR-106E thrusters. The burn duration was 19.1 seconds and it consumed approximately 0.72 kg of propellant.

During the interplanetary transit, only the <u>first</u> two of the four planned spacecraft TCMs were necessary. Although the encounter altitude at Mars closest approach increased slightly (~25 km), TCM-3 and TCM-4 was ultimately canceled as the inbound flight path to Mars remained very stable. This is a significant interplanetary navigation achievement and is owed to the attention to detail in spacecraft and dynamical modeling. This also saved about two-thirds of the planned propellant expenditure for interplanetary cruise. With the spacecraft on an acceptable flight path for Mars encounter and the MOI maneuver, neither one of the two emergency maneuvers were needed.

Spacecraft Activities

Transition to high gain antenna (HGA) occurred on September 22nd, 43 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 used a rate of 550 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 were performed in order to calibrate and determine the performance of various spacecraft subsystems relative to models or predicts. A complete listing of the planned spacecraft calibrations is shown in Table 3.

Table 3: Planned Spacecraft Activities for Cruise

Calibration Activity	Date	Subsystem/Instruments	Objectives
HGA Boresight & Gimbal Calibration	Sept 9	Telecom	Necessary for high data rates
Thruster Calibration	Sept 15	GNC	Determine translational delta-v imparted by thrusters during AMDs
Switch to HGA and Ka-band pass 1 of 10	Sept 22	Telecom	Test Ka-band link
HiRISE to Star Tracker Alignment	Oct 3-5	HiRISE, GNC	Determine the inertial pointing accuracy
Gyro to Star Tracker Alignment	Oct 26	GNC	Needed to support precision targeting Verify inertial pointing
SRP and Gravity-2 Calibrations	Dec 29-Jan 3	GNC	Measure the torque as a result of SRP, and its impact on NAV

Instrument Activities

In order to fully characterize instrument performance, in-flight calibrations of the payloads were performed. Table 4 summarizes the planned payload cruise calibrations as well as the participating instruments and their objectives.

Many of the instrument calibrations were designed to achieve several different objectives. Radiometric calibrations measured 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. The HiRISE images of a stellar target were used to characterize jitter disturbances from other payloads. Additionally, both SHARAD and Electra characterized the orbiter Electromagnetic Interference environment in receive-only ("sniff") mode.

Table 4. Planned Payload Activities Cruise

Calibration Activity	Date	Instruments	Objectives
MARCI UV	Aug 15	MAR	Radiometric in the UV bands
L+18 Instrument Checkout	Aug 29-30	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	Sep 7-8	HIR, CTX, ONC, IMUs and Star Trackers	HiRISE and CTX: stray light geometric, radiometric. ONC: geometric
MCS Solar Target Calibration I	Sep 12	MCS	Calibrate the MCS Solar Target
Electra/Stanford Test	Sep 21-22	EUT	Characterize antenna pattern with stable Earth source
Gravity-1 Calibration	Nov 14-20	DSN tracking in support of TCM-2	Create baseline far from gravity fields
ONC-2 Calibration	Nov 29	ONC	Geometric
Stellar-1 Calibration	Dec 6-7	HIR, CTX, IMUs and Star Trackers	Geometric, Radiometric (Note: Calibration event deleted; components of this activity were combined with Stellar-2 Calibration)
Stellar-2 Calibration	Dec 13-14	HIR, CTX, SHR, MCS, CRM, EUT, MAR, IMUs and Star Trackers	Geometric, Jitter, EMI
MCS Solar Target Calibration II	Dec 19	MCS	Calibrate the MCS Solar Target
Gravity-2 Calibration	Dec 29-Jan 3	Uses s/c tracking data	Create baseline far from gravity fields

The turn-on and initial check out of the instruments was performed from August 29 – 30, 2005. The instruments were powered sequentially and all instruments turned on and returned instrument housekeeping data. Most objectives were achieved, although the HiRISE checkout had to be repeated on September 2 after an adjustment of the turn-on sequence. Figure 8 shows the HiRISE image of the moon taken during its Lunar Calibration event on September 7, 2005.

Figure 8. HiRISE image of Earth's moon

Figure 9. Artist rendering of the MRO spacecraft during the MOI burn

Approach and Orbit Insertion Phase

The Approach and Orbit Insertion Phase extended from two months prior to Mars Orbit Insertion (MOI), through MOI (March 10, 2006), and until the orbiter was checked out and ready to begin aerobraking. During most of this phase of the mission, the DSN was scheduled for continuous coverage with the frequency of delta-DOR measurements for navigation increased. During the approach to Mars, MRO prepared for the final TCMs (TCM-3, TCM-4), prepared for the emergency TCMs (TCM-5a, TCM-5b), completed readiness tests for the MOI maneuver sequence, and conducted the Optical Navigation Experiment. As mentioned earlier, none of the TCMs during this time period were needed. As a general policy, the scheduling of spacecraft and payload activities was not allowed during this time period. This policy was put in place so that the final preparations for MOI, an MRO mission critical event, would not be hindered by ancillary activities and that the spacecraft configuration would be stable for MOI ground-based sequence testing.

During the last 30 days of the approach phase, MRO conducted the Optical Navigation experiment. This involved 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 accurately determined the position of the orbiter. These measurements were compared to the traditional radio frequency (RF) measurements like delta DOR (differenced one-way ranging). Assessment of the results of this experiment is underway.

As a strategy to make MOI single fault tolerant, the MRO Project opted to start the MOI maneuver two minutes early. This decision cost an extra 10 meters per second of ΔV to compensate for the non-optimal burn time but it afforded the fault protection subsystem adequate time to recover from a potential single event upset, should it occur, and resume the burn from the previous known attitude.

Upon arrival at Mars on March 10, 2006, the spacecraft performed its MOI maneuver using its six main 170 N engines. MOI burn inserted the spacecraft into an initial, highly elliptical capture orbit with a period of 35.5 hours and a periapsis of 426 km. The ΔV required to accomplish this critical maneuver was 1000 m/s and the burn duration was approximately 27 minutes. For most of the burn, the orbiter was visible from the Earth-based DSN stations. During the last 5 minutes of the burn, the signal was occulted as the orbiter went behind Mars and remained so for approximately 30 minutes. At capture, the orientation of the ascending node was 8:30 PM Local Mean Solar Time (LMST). The node of the capture orbit node was selected such that aerobraking operations would be completed prior to the start of the solar conjunction blackout. Figure 9 shows an artist's rendering of the MOI burn.

Post MOI Imaging

After successfully completing the MOI activities, the mission conducted its post MOI imaging campaign. Four instruments, MARCI, HiRISE, CTX, and MCS were turned on and engineering quality images were obtained. The first three instruments listed above acquired images at a height of approximately 2489 km above the surface or almost ten times the final science orbit. The image quality was excellent. Figure 10, 11 and 12 show representative images from those instruments, respectively. The fourth instrument, MCS, took images of Mars from apoapsis and also a "self portrait" of the spacecraft nadir deck, Figures 13A and 13B.

Figure 10. A sample of a HiRISE image with resolution at 2.5 m/pixel.
http://marsoweb.nas.nasa.gov/HiRISE

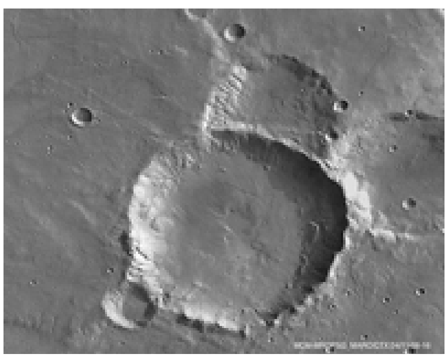

Figure 11. CTX image of Mars with resolution at 60m/pixel.
http://www.msss.com/mro/ctx/index.html

Figure 12. MARCI image of Mars
www.msss.com/mro/marci/index.html

Figure 13A. MCS image of Mars' north polar region taken through different filters
www.planetary.org/projects/mars_climate_sounder

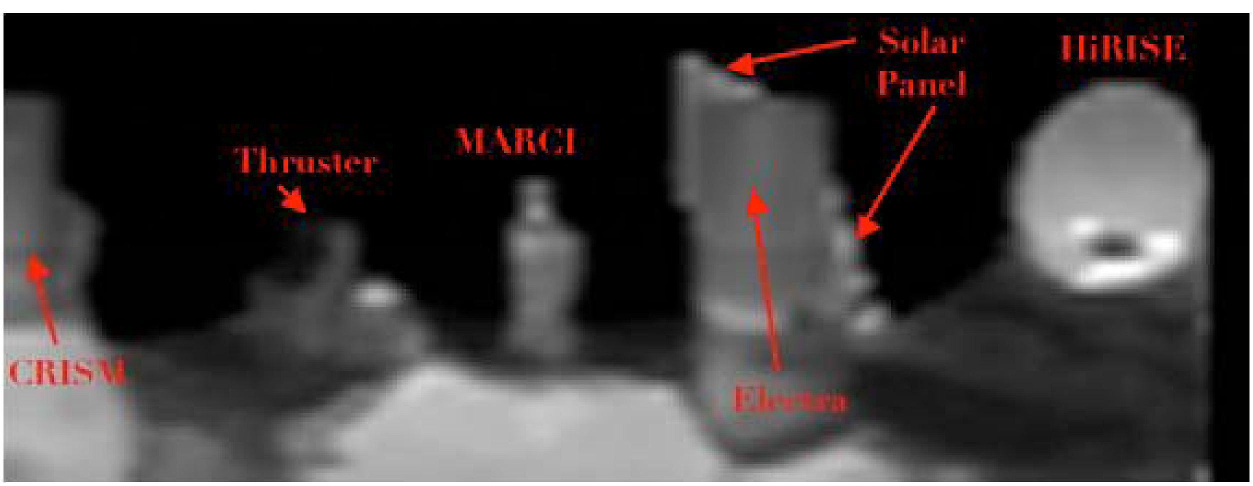

Figure 13B. MCS image of MRO spacecraft nadir deck.
www.planetary.org/projects/mars_climate_sounder

Aerobraking Phase

Aerobraking is a technique that uses friction between the spacecraft surfaces and the molecules in the upper Martian atmosphere to slow the spacecraft velocity. The usage of aerobraking allowed MRO to lighten its overall fuel (and thus launch) load by almost 600 kg; aerobraking provided MRO an equivalent DV capability of nearly 1200 m/s. It consisted of three distinct phases: a walk-in phase, a main phase, and a walkout phase.

On March 30, 2006, MRO started its approach toward the Martian atmosphere departing the capture orbit established by its MOI maneuver. This was accomplished by performing a series of maneuvers that gradually lowered periapsis altitude. The first maneuver lowered periapsis to an altitude of 333 km. This was immediately followed by a maneuver on the subsequent orbit that lowered periapsis to an altitude of 239 km. On April 3, a third maneuver was performed allowing MRO to have its first encounter with the Martian atmosphere. That encounter occurred at an altitude of 147 km. As expected, very small atmospheric (drag) forces were detected on the spacecraft by its accelerometers. Navigation confirmed the effect of the drag forces on the orbital parameters by analyzing radiometric data. This initial series of maneuvers was a planned activity testing the spacecraft's aerobraking maneuver and drag pass re-orientation capabilities. As the spacecraft's performance was as expected, MRO commenced aerobraking operations with the "walk-in" phase. Figure 14 shows an artist rendering of the spacecraft conducting a drag pass.

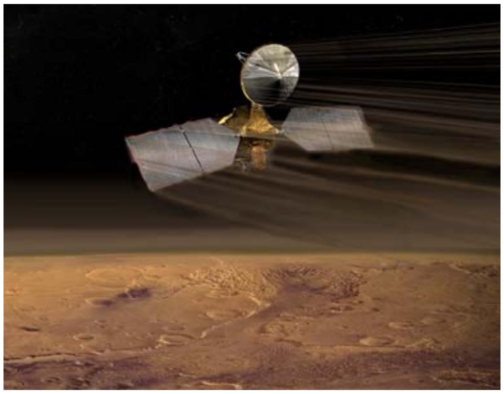

Figure 14. Artist rendering of the MRO spacecraft conducting a drag pass during aerobraking

During the walk-in phase, the spacecraft continued contact with the atmosphere every orbit as the periapsis altitude of the orbit was slowly lowered. This phase continued until the freestream heating rate limits required for main phase, or steady state aerobraking, were established at an altitude of 105.3 km. Three more maneuvers were required in order to reach the freestream heating rate limits desired for main phase.

During main phase, large-scale orbit period reduction occurred as the orbiter was guided to freestream heating rate limits. Figure 15 shows the actual orbit period change over the course of aerobraking. In order to adjust the freestream heating rate limits and the associated orbit period reduction rates, small "corridor control" maneuvers were performed.

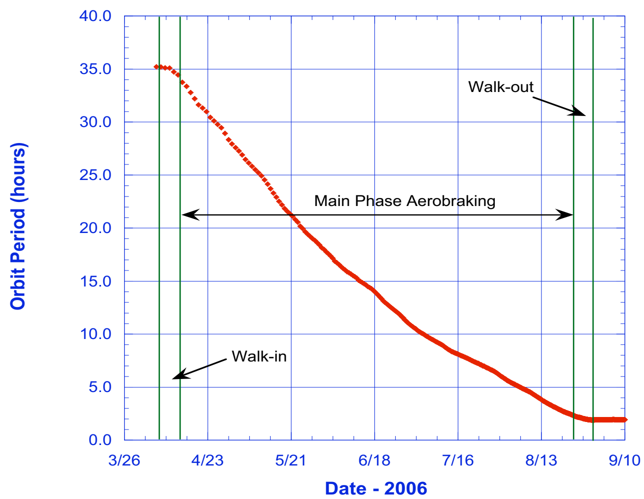

Figure 15. Orbit Period Change during Aerobraking

Main phase lasted for approximately 4.5 month and continued until the orbit lifetime of the orbiter reached 2 days. (Orbit lifetime is defined as the time it takes the apoapsis altitude of the orbit to decay to an altitude of 300 km.)

When the orbit lifetime of the orbiter reached 2 days, the aerobraking walkout phase began. During the walkout phase, the periapsis altitude of the orbit was slowly increased to maintain the minimum 2-day orbit lifetime. On August 30, MRO reached orbital conditions sufficient for aerobraking termination and propulsive establishment of the primary science orbit. At that time, MRO had reached an apoapsis altitude of 486 km with an ascending node near 3:10 pm LMST (local mean solar time). As a result, the orbiter terminated aerobraking by propulsively raising the periapsis of its orbit out of the atmosphere. This was accomplished using the six 22 N MR-106E thrusters. The aerobraking termination maneuver raised periapsis to an altitude of 215 km. The maneuver magnitude was 25.0 m/s and it had a burn duration of 5.8 minutes. It should be noted that in the walkout phase, the close approach distances to the Odyssey, MGS (Mars Global Surveyor), and Mars Express spacecraft were closely monitored. On more than one occasion, the MRO spacecraft performed a collision avoidance maneuver increasing its relative range to the Odyssey spacecraft. During the entire course of aerobraking, a total of 27 maneuvers were executed for spacecraft trajectory control.

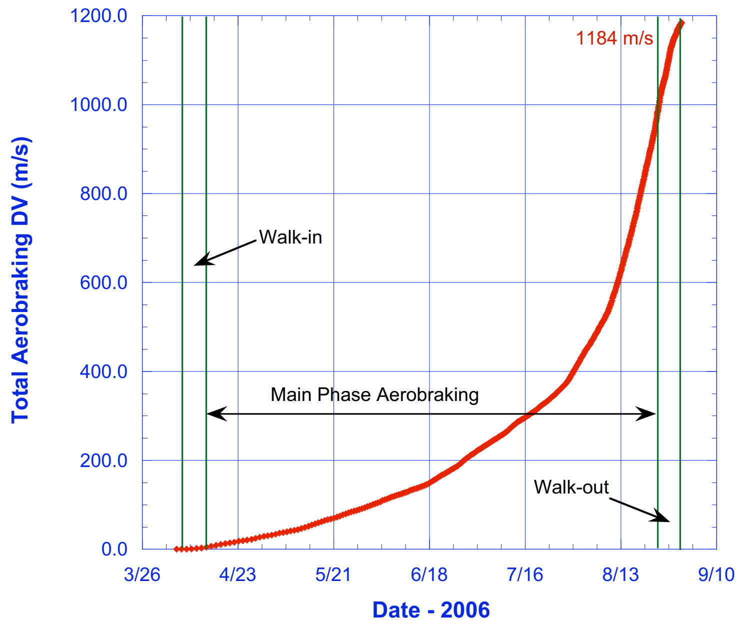

Figure 16 – Aerobraking DV – Cumulative as a Function of Date

The original aerobraking plans called for nearly 5.5 months of operations with 560 drag passes to be performed. In order to allow more time for Transition activities and to prepare for spacecraft operations during the solar conjunction time period, the pace of aerobraking was quickened. As a result, aerobraking was completed in 5 months with only 426 drag passes. During the aerobraking time period, the apoapsis altitude of MRO's orbit was reduced from 44982 km to 486 km as the orbit period was reduced from 35.5 hours to 1.91 hours. The actual DV saved by MRO due to aerobraking was 1184 m/s. The majority of that benefit was not realized until the last month of aerobraking. That effect is clearly evident in Figure 16.

Transition to Science Operations

Once aerobraking was terminated, MRO performed a series of propulsive maneuvers to establish the primary science orbit. Both of these orbit adjust (OA) maneuvers were performed using the six 22 N MR-106E thrusters. The first maneuver (OA-1) raised periapsis altitude and adjusted inclination. The inclination adjustment was designed so that the LMST of the ascending node would drift to the desired 3:00 pm LSMT value for the science orbit in about two months. OA-1 was performed on September 5 and had a maneuver magnitude of 15 m/s. Its burn duration was 3.5 minutes. The second maneuver (OA-2) lowered apoapsis and rotated the line of apsides to that desired for the primary science orbit. OA-2 was performed on September 12 and had a maneuver magnitude of 53.5 m/s. Its burn duration was 12.5 minutes. Because of the drifting LMST condition, another small burn will be performed to stop the drift. That maneuver is currently slated for execution on November 15; its magnitude is expected to be near 7 m/s.

With the science orbit essentially established, the Project completed commissioning of the engineering bus and the science instruments. Engineering activities included performance and positioning calibration of the high gain antenna, flight software upgrades, and nadir positioning maneuvers. For the instruments, they included deployment of the 10 m long SHARAD antenna and check out of its transmitter hardware and deployment of the CRISM cover and first light into its spectrometer. After approximately a month of activities, the full suite of instruments was turned on and science performance of the instruments in flight was assessed. Also the ground-based science planning techniques used by the science and spacecraft teams were tested. In early October, four of the instruments were safed for the month long solar conjunction time period. Two instruments, MARCI and MCS, continued to acquire data during this period in order to start the year long observational period required by these investigations. A summary of the transition activities is shown in Figure 17.

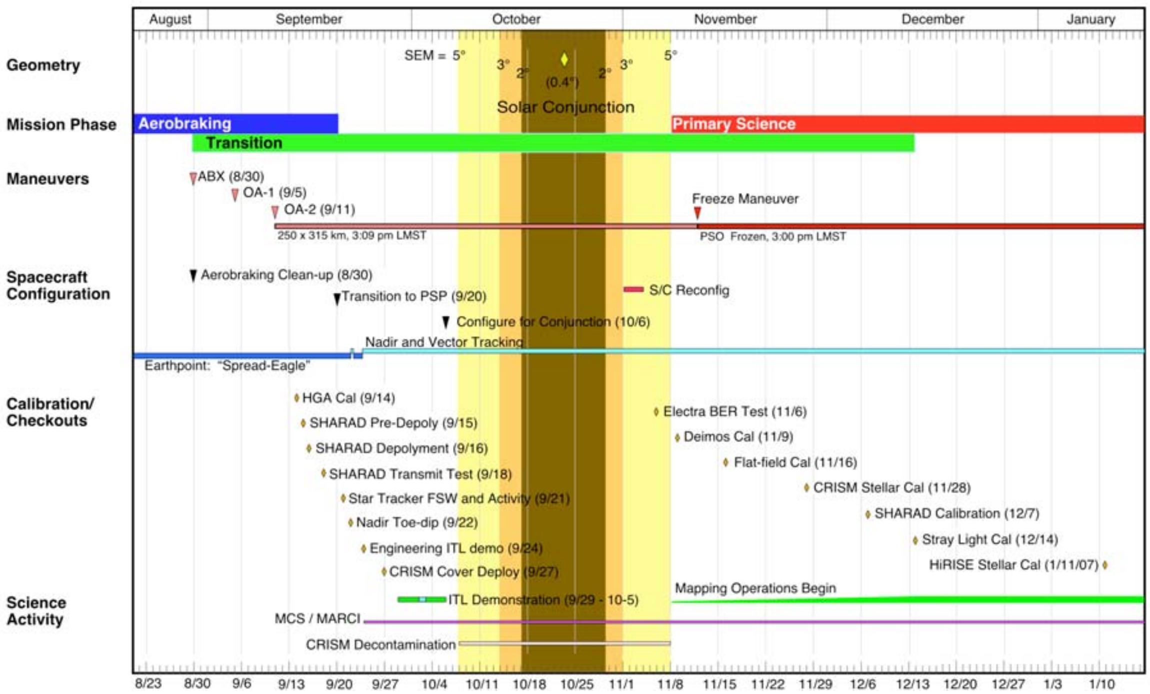

Figure 17. Transition Phase activities – as flown

5. MISSION DESCRIPTION - SCIENCE OPERATIONS AND RELAY

This section will provide a description of the primary science and relay phases of the MRO Mission. This section includes a description of the primary science orbit, the mission phase timelines, and the operations strategy planned for science data acquisition and return.

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. 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 observation 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, MRO 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.

Mission Timelines

To synthesize the mission design, top-level timelines have been developed for each mission phase. Figure 18 shows the timeline for the Primary Science Phase. It includes the aerobraking termination events, the transition to the PSO, solar conjunctions, maneuver events, orbiter checkouts and calibrations, Mars seasons and geometry, DSN tracking levels, and the launch and arrival dates for the first Mars Scout Mission, the Phoenix Lander. MRO will use its high resolution science instruments to support the Phoenix mission by performing landing site selection support. In addition, MRO will use its Electra telecom package to (a) monitor the lander’s approach trajectory and its EDL (entry, descent, and landing) event, and (b) relay data to/from the Phoenix lander once it is on the surface. Phoenix surface observations are expected to last for five months.

Figure 19 shows a timeline for the Relay Phase. Also shown are solar conjunctions, maneuver events, Mars seasons and geometry, DSN tracking levels, and the typical arrival periods for the 2009 Mars mission opportunities. Currently, the Mars Science Laboratory (MSL) is proposed for launch in 2009, with arrival in 2010, during the MRO Relay Phase. MSL will need MRO to provide and characterize candidate landing sites using observations during the MRO PSP. The End-of-Mission (EOM) is shown at its required date of December 31, 2010 just prior to the third solar conjunction of the mission. If needed, the orbiter will perform a propulsive maneuver to place itself in a higher orbit to enable extended mission operations.

Operations Planning

To accomplish its science objectives, MRO will conduct an integrated program of three distinct observational modes:

- Daily global mapping and profiling
- Regional survey, and
- Globally distributed targeting

These observation modes will be intermixed and often overlapping. Some instruments have more than one observational mode. In addition, many targeted observations will involve nearly simultaneous, coordinated observations by more than one instrument. This section describes current operations planning activities performed for MRO.

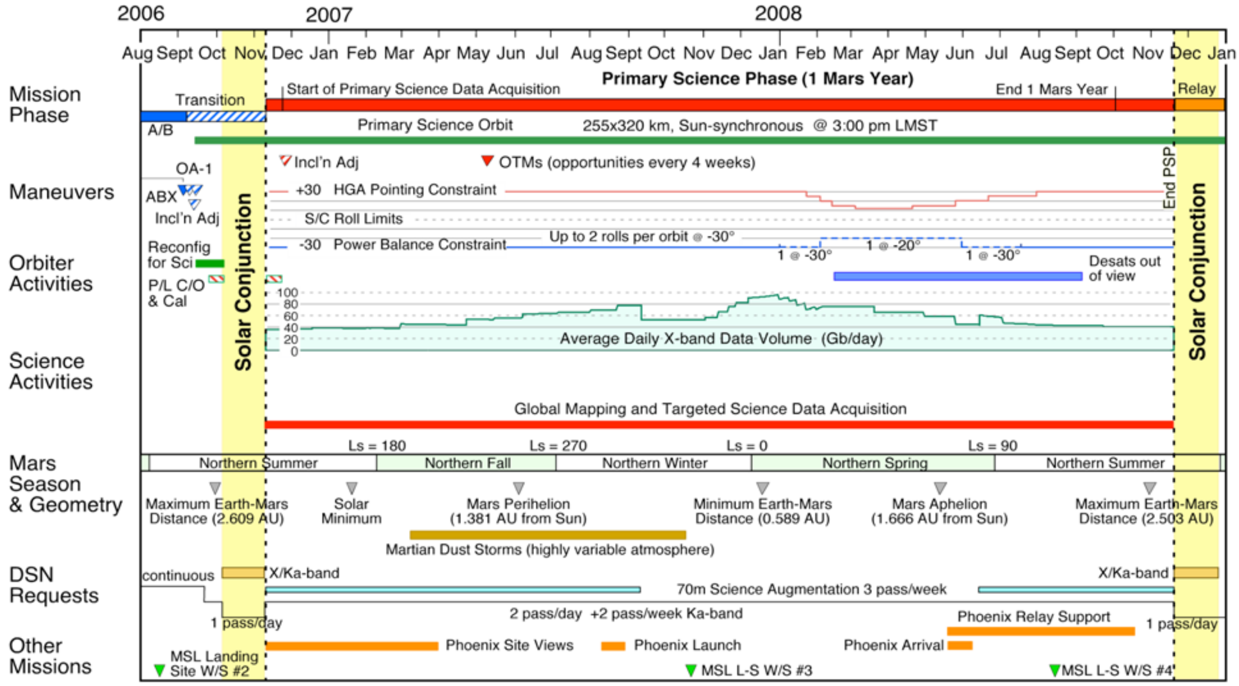

Figure 18. MRO Mission timeline – Primary Science Phase

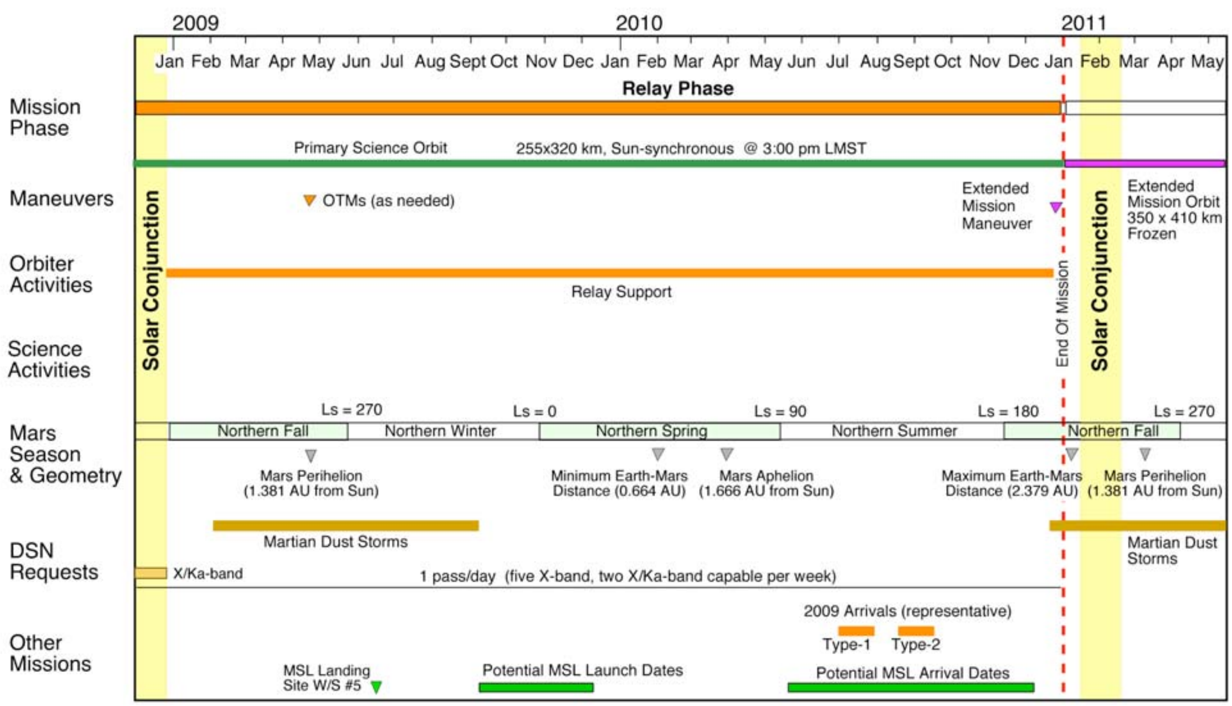

Figure 19. MRO Mission timeline – Relay Phase

Observation Modes

The science investigations are functionally divided into daily global mapping and profiling, regional survey, and globally distributed targeting investigations. The global mapping instruments are the MCS and the MARCI. The targeted investigations are HiRISE, CRISM, and CTX. The survey investigations are CRISM and CTX (in survey modes), and SHARAD. The global mapping instruments require nadir pointing, low data rate, and continuous or near-continuous operations. The global mapping investigations are expected to use less than 5% of the expected downlink data volume. The targeted and survey instruments are high data rate instruments and will require precise targeting in along-track timing and/or cross-track pointing for short periods of time over selected portions of the surface. It is expected that more than 95% of the available downlink data volume will be used for targeted and survey investigations. All instruments can take data simultaneously (including Electra).

Target Planning Strategies – Interactive and Non-interactive Observations

The science data acquisition strategy is predicated on the Primary Science Orbit characteristics, the objectives of the selected science investigations (instrument and facility teams), and the available orbiter resources and capabilities. Investigation priorities, targeted observations and data allocations will be coordinated in advance by the science teams, culminating in meetings every four weeks of the Target Acquisition Group or TAG, which includes membership from the PSG and representatives of the Mars Exploration Program. The TAG confirms plans for the immediate science and sequence planning cycle. For the subsequent planning cycle the TAG will consider changes in planning guidelines, changes in instrument data allocations, and will coordinate opportunities and guidelines for survey and targeted observations.

Off-nadir target selections are made every four weeks by the TAG for the coming 28-day period, with an update after two weeks. Because navigation prediction accuracy will not be sufficient for pre-selecting 4 weeks worth of targets, a special "mini-TAG" will occur 2 weeks after every TAG meeting. The function of that meeting is to adjust targets for the second half of the 4-week period based on guidelines and priorities set at the prior TAG meeting.

There are two fundamental types of science observations: Non-Interactive Observations and Interactive Observations. Non-interactive observations do not require the spacecraft or other instruments to change modes or support them. Investigation teams plan their non-interactive observations independently of other investigations. Since the spacecraft is always nadir pointed, non-interactive observations can be made anytime unless there are interactive observations that are in conflict.

Interactive observations are those that require the spacecraft or another instrument to change its mode. Examples of this include off-nadir targeting (spacecraft rolls), observations that require suspension of MCS or solar array motion, and nadir observations that require no slews while observing. Interactive observations are always planned and coordinated through the science planning process and ratified by the TAG.

The science planning process coordinates all interactive observations, and verifies that sufficient resources (pointing, data volume) are available for all of the interactive observations and that enough data volume resources are available for the independent non-interactive observations. At the end of the science planning process and the TAG meeting, a conflict-free set of interactive observations are provided for sequence implementation.

The non-interactive nadir observations are commanded via non-interactive payload commands (NIPC) and sent independently of orbiter sequences up to a few hours or days before the observation is made. Non-interactive observations could be high or low resolution images, survey observations, or global mapping observations.

Interactive observations are sequenced and coordinated with the orbiter background sequencing process. Integrated Target Load, (ITL) files are generated that specify the Mars relative pointing parameters. This allows pointing software on the orbiter to calculate the appropriate pointing direction for the time of the observation based on the most recently uploaded ephemeris files. Coordination of the timing and pointing of the various instruments involved in a targeted observation is controlled by the orbiter via on-board sequence blocks. Updates to the instrument specific observation parameters can be made via NIPC days or up to hours prior to the observation

In order to reduce pointing errors resulting from navigation uncertainties, the orbiter will use an ephemeris driven on-board pointing algorithm. The number of off-nadir targets per day is constrained to 20 per day or 2 per orbit for planning purposes. The orbiter is capable of acquiring up to 4 targets per orbit if there is a compelling need. More than 1000 targeted observations will be made during the primary science phase.

An example "day-in-the-life" of the orbiter is shown in Figure 20. All investigations are represented except OPNAV and Accelerometer investigations since they operate in earlier mission phases. Activities scheduled in the background sequence are shown. DSN coverage is shown with the current baseline tracking durations. Gravity Doppler data is collected whenever the orbiter is in contact with the DSN. Reaction wheel desaturation events will be scheduled during DSN tracking to increase navigation reconstruction accuracy and Gravity science data quality. A representative pattern of off-nadir targets sequenced in the ITL is shown. Nadir observations can be sequenced in the ITL or by ground built sequences. SHARAD is generally constrained to operate during eclipse on orbits that have no DSN coverage. High Gain Antenna (HGA) rewinds are shown. Note that Solar Array tracking and MCS gimbal motions may need to be suspended during the highest resolution HiRISE targeted imaging if stability concerns require it.

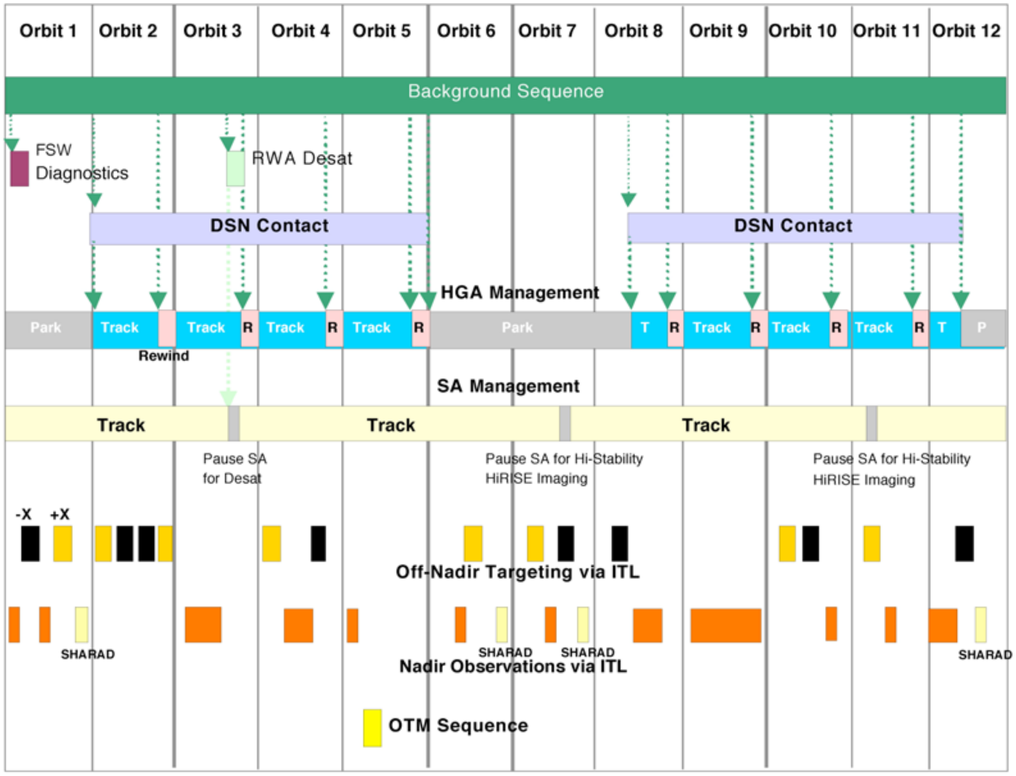

Figure 20. Orbiter Day-in-the-Life

Data Return Strategy

Data acquired by the MRO science instruments will be stored on the Solid State Recorder (SSR). The orbiter Command and Data Handling subsystem will prepare and/or process the science data and store it as downlink telemetry frames in temporary SSR buffers queued for downlink via the Small Deep Space Transponder (SDST). Data will be acquired based on data volume allocations that match the daily downlink data volume capability of the orbiter-DSN link. All acquired data will be transmitted to the DSN.

The orbiter will be able to target as many as 20 sites per day, but a single target may yield from 2 to 20 Gbits. Therefore, the possible number of targets under consideration for investigating varies considerably over the course of the mission. Data acquisition and downlink are asynchronous. Data management and downlink priority are independent of collection strategy or order.

In addition to the baseline two 8-hour tracks per day during the science phase, 70m coverage will be requested. 70m passes will be used to augment the baseline plan, allowing for additional data return during periods where the Earth-Mars range is near its maximum. The 70m passes will be scheduled three times per week from November 2005 to June 2007 and from February 2008 to November 2008. Ka-Band capable 34m-BWG antennas will be requested twice per week for the entire primary science phase as part of a Ka-band telecommunications technology demonstration. Since gravity science on MRO uses two-way x-band Doppler data, any tracking shared with other missions using Multiple Spacecraft Per Aperture (MSPA) configurations will have to be carefully coordinated with DSN schedulers.

The MRO spacecraft has been designed to provide at least 500 kbps at maximum range (2.67 AU) to a 34m BWG station using Turbo 1/3 encoding. At closer ranges the signal strength will be greater and a higher data rate will be possible. MRO will also have a variety of coding schemes available to maximize the rate capability at a particular range. The orbiter and the DSN have several constraints on the symbol rates, data rates, and signal bandwidth used at a given time.

Data Volumes from MRO are calculated from the data rate at a particular time, and from the amount of time available for downlink. The time available for downlink is a function of orbit period, occultation duration, lockup time assumptions, tracking time assumptions, and the duration of orbiter activities that prevent downlink (e.g., HGA off-pointing). Data rate and downlink duration vary day to day. Figure 21 shows the baseline daily data volume for the Primary Science Phase. Figure 22 shows the cumulative data volume over the course of the Primary Science Phase. Additional information explaining the Mission Operations architecture can be round in Reference 5.

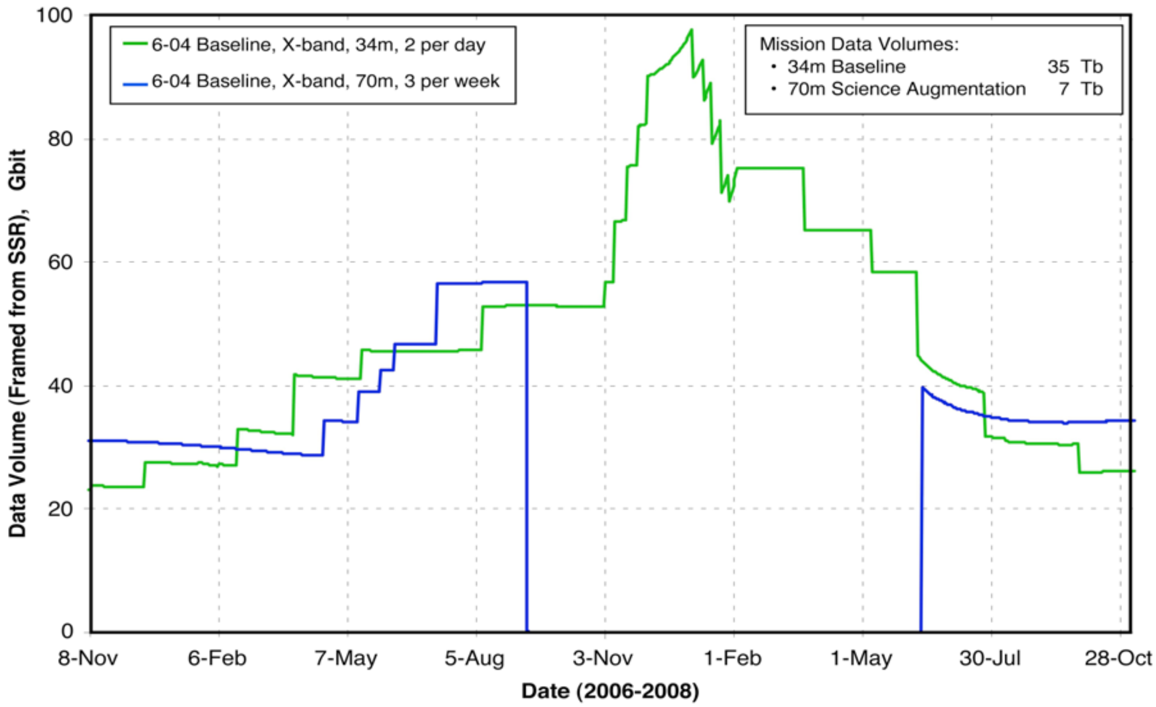

Figure 21. Baseline daily data volume for Primary Science Phase

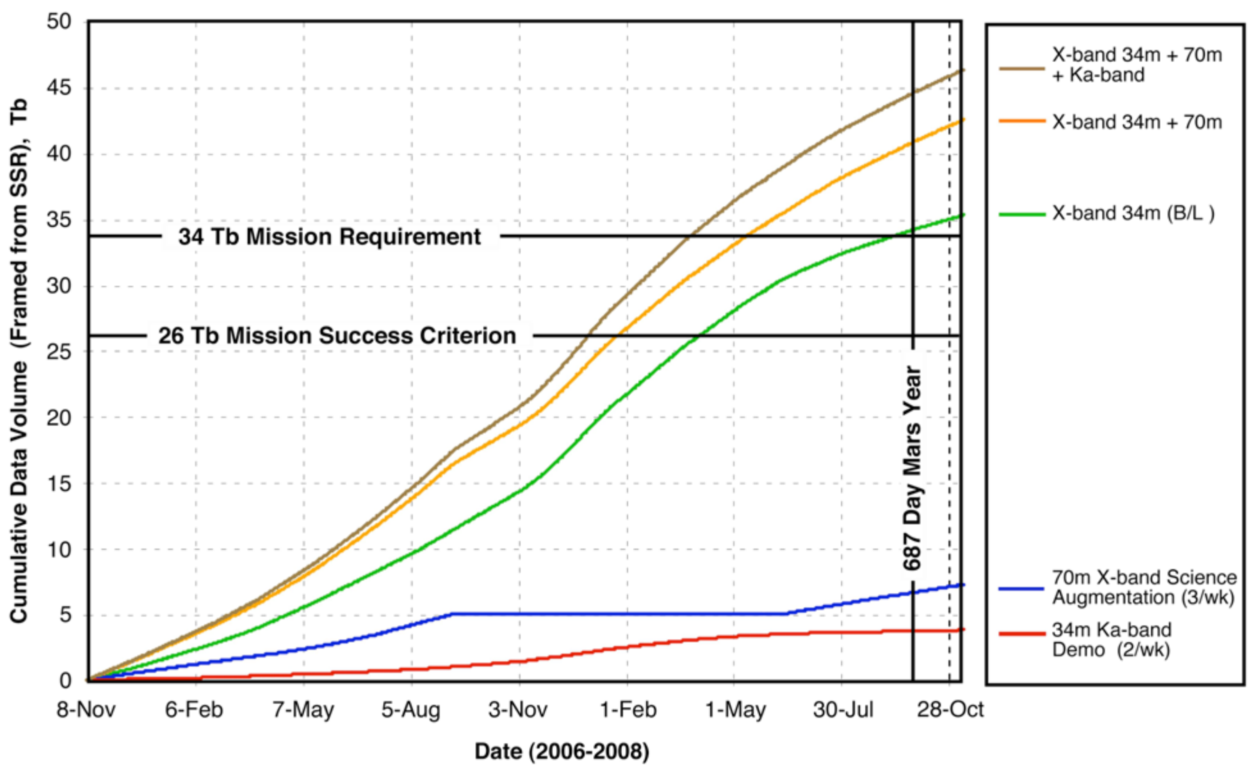

Figure 22. Expected cumulative data volume during the Primary Science Phase

6. IMPLEMENTATION AND SCHEDULE

The MRO mission is managed by the Jet Propulsion Laboratory and its implementation relies heavily on the capabilities of industry and academia. Lockheed-Martin Astronautics in Denver, CO was selected in October 2001 to develop the spacecraft bus, perform payload accommodations, and provide launch and operations support. In November 2001, NASA Headquarters selected the major elements of the science payload via the Announcement of Opportunity process. In May 2002, KSC selected the Lockheed-Martin Astronautics Atlas V 401 as the launch vehicle for MRO mission. The system-level Preliminary Design Review (PDR) was accomplished in July 2002 with the formal NASA confirmation of the MRO given in September 2002. Entering its implementation phase, MRO successfully accomplished its system-level Critical Design Review (CDR) in May 2003. This was followed by a successful ATLO (Assembly, Test, and Launch Operations) Readiness Review in March 2004 and the initiation of ATLO activities at Lockheed Martin facilities in Denver, CO. The Orbiter was shipped to the Kennedy Space Center in May 2005 and shortly thereafter began its processing for launch. In August 2005, the spacecraft was launched from Cape Canaveral Air Force Station, culminating a successful three-month launch campaign.

Establishment of the primary science orbit at Mars occurred in September 2006. The MRO mission is now focusing on science data acquisition as it enters its primary science phase. Science operations will be conducted for at least one Martian year (~two Earth years). This will be followed by relay operations until the planned end of mission in December 2010. Propellant reserves are believed to be sufficient so that the eventual consideration of a mission extension is possible.

7. SUMMARY

MRO is a flagship mission of the Mars Exploration Program.. The MRO spacecraft and its scientific payload reflect a state of the art design for planetary exploration. The MRO spacecraft has arrived on station at Mars following a 13-month journey that included seven months of interplanetary flight and five months of aerobraking at Mars. The orbiter has successfully completed all of its deployments and is healthy and functioning properly as it orbits the Red Planet every 117 minutes. It is currently in the process of being readied for its primary science mission. Initial operation of the science instruments has shown that this mission will greatly enhance our understanding of Mars by returning new, high resolution scientific observations. 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.

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9. BIOGRAPHY

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

Jim Graf received a BSE from Princeton University in 1972 and an MS from Colorado State University in 1976. He has been employed in various space-related developments for 28 years, ranging from the development of ion thruster technology to the management of the Quick Scatterometer Mission, an Earth orbiting satellite that was ready to launch within one year of formal go-ahead. He is the recipient of NASA's Outstanding Leadership Medal and an Aviation Week's 1999 Laurel for Space. Currently, Mr. Graf is the Project Manager of the Mars Reconnaissance Orbiter Project.

Dr. Richard Zurek graduated from Michigan State University with a BS in Mathematics in 1969 and received his Ph.D. in Atmospheric Sciences from the University of Washington (Seattle) in 1974. Following one-year post-doctoral appointments at the National Center for Atmospheric Research and at the University of Colorado in Boulder, Colorado, he went to work at JPL, where he has been employed since 1976. Dr. Zurek is currently the Project Scientist of the Mars Reconnaissance Orbiter Project.

Howard J. Eisen received a B.S. and an M.S. in Aeronautics and Astronautics and a B.S. in Physics from M.I.T. He has worked on a variety of missions orbiting the Earth and landing on Mars including the Mars Pathfinder Sojourner Rover. He is the recipient of the JPL Award for Excellence in Leadership and has twice been awarded the NASA Exceptional Achievement Medal.

Benhan Jai received an MS in Computer Engineering from the University of Southern California in 1985. Since joining JPL in 1985, he has participated in the development of the Mission Operations and Ground Data System for several planetary missions. Currently, Mr. Jai is the Mission Manager of the Mars Reconnaissance Orbiter Project.

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