AIAA SPACE 2007 Conference & Exposition
18 - 20 September 2007, Long Beach, California

AIAA 2007-6090



# An Overview of Mars Reconnaissance Orbiter Mission, and Operations Challenges

Ben Jai[1], Daniel Wenkert[2], Brian Hammer[3], Magdi Carlton[4], Dan Johnston[5]
*Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, 91109*

Tim Halbrook[6]
*Lockheed Martin Space Systems Company, Denver, Colorado, 80125*



**[Abstract] The Mars Reconnaissance Orbiter (MRO) was launched on August 12, 2005 by an Atlas V launch vehicle from Cape Canaveral Air Force Station, and arrived at Mars on March 10, 2006. MRO carries a rich set of science instruments to Mars, and provides global and regional survey, and targeted observations. In addition, a set of engineering instruments providing optical navigation, Ka band telecommunication and ultra-high frequency (UHF) relay services to future Mars missions are part of the MRO payload. After arriving at Mars on March 10, 2006, MRO was captured in a 35.5 hour orbit around Mars. On March 23, 2006, MRO had begun its aerobraking operations to reduce its orbit time to less than two hours and reach the preferred ascending node time of 3:00 pm Mars Local Time. On August 31, 2006, an aerobraking termination maneuver was carried out onboard MRO in order to finish the aerobraking phase, and a set of maneuvers were conducted to finalize the Primary Science Orbit (PSO). A set of transition activities, including engineering and science instrument calibrations and a weeks worth of "science practice" were carried out during this period as well, immediately prior to MRO's entrance into the solar conjunction period. During the Primary Science Phase (PSP) of the mission, the MRO operations teams were presented with two major challenges – unprecedented high data rate and data volumes, and complex science planning and resource sharing. MRO has the capability to communicate with earth at a maximum of six Megabits per second (Mbps), which is more than 50 times any previous Mars missions. With the current Deep Space Network (DSN) contact schedule of 19 eight-hour tracks per week, the baseline mission plan is for MRO to return 34 Terabits of raw science data during the two-year primary science phase. Each of the science instruments has its unique requirements for global mapping, regional survey, and targeted observations. Some instruments prefer nadir-only observations, while others require off-nadir observations (especially for stereo viewing). The requirements from these Mars viewing instruments presented a significant challenge for the operations team to design the complex science planning and resource sharing and allocation process. In addition, because of the high resolution instruments, navigation accuracy requirement at this low orbit became critical. This paper describes the implementations put forth by MRO to solve these challenges, and some of the subsequent results.**

## I. Introduction

The Mars Reconnaissance Orbiter (MRO) was launched from Cape Canaveral, Florida using a Lockheed Martin Atlas V-401 launch vehicle on August 12, 2005. The transit time to Mars was approximately seven months. During this period, a series of trajectory course corrections were carried out, and orbiter payloads were checked out and a series of instrument and spacecraft calibrations performed.

[1] Mission Manager, MRO Project, 4800 Oak Grove Drive, Mail Stop 264-535.
[2] Payload Operations Support Team Chief, MRO Project, 4800 Oak Grove Drive, Mail Stop 264-535.
[3] End to end Data Accountability Team Chief, MRO Project, 4800 Oak Grove Drive, Mail stop 264-535.
[4] Ground Data System Element Manager, MRO Project, 4800 Oak Grove Drive, Mail Stop 264-535.
[5] Deputy Mission Manager, MRO Project, 4800 Oak Grove Drive, M/S 264-535.
[6] Senior Manager, Systems Engineering, 12257 South State Highway 121, Mail Stop S1008.

After arriving at Mars in March 2006, the MRO orbiter had been propulsively inserted into a highly elliptical capture orbit with a period of 35 hours. The orbiter used aerobraking techniques to reduce its orbit to near that needed for science observations, and performed aerobraking termination maneuver on August 30, 2006. After the end of aerobraking, several orbit adjustment maneuvers were performed to adjust the periapsis and apoapsis to the desired Primary Science Orbit (PSO) orbital characteristics, and a small maneuver was also performed to stop the Local Mean Solar Time (LMST) clock drift. The 255 km x 320 km PSO is a near-polar orbit with periapsis frozen over the South Pole. It is sun-synchronous with an ascending node orientation that provides a LMST of 3:02 p.m. at the equator. After MRO was settled in the desired PSO, the Shallow Radar (SHARAD) antenna and the cover for the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM), were successfully deployed. Subsequently, all science instruments were checked out, and an 8-day operation similar to the Primary Science Phase (PSP) was conducted to flush out potential operations and data systems problems prior to the beginning of the PSP. This gave the operations team an opportunity to fix any problems that arose during solar conjunction.

The Mars Reconnaissance Orbiter mission has the primary objective of placing a science orbiter into Mars orbit to perform remote sensing investigations that will:

- advance our understanding of the current Mars climate, of 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.
- identify sites of possible aqueous activity indicating environments that may have been or are conducive to biological activity; and thus, identify and characterize sites for future landed missions.

See Table 1 for the complete listing of science instruments onboard the MRO spacecraft.

Table 1. Science Investigation Objectives

| ***Instrument*** | ***Type*** | ***Measurement Objectives*** | ***Science Goals*** | ***Attributes*** |
|---|---|---|---|---|
| **CRISM** **(Compact Reconnaissance Imaging Spectrometer for Mars)** | High-Resolution Imaging Spectrometer | Hyper-spectral Image Cubes<br>514 spectral bands,<br>0.4-4 microns, 7 nm resolution<br>*From 300km:* 20 meters per pixel, 11 km swath | Regional & Local Surface Composition and Morphology | Key: Moderately High Spectral & Spatial Resolution<br>Targeted & Regional Survey<br>Very High Data Rate |
| **CTX** **(Context Camera)** | Mono-chromatic Context Camera | Panchromatic (minus blue) Images<br>*From 300km altitude:*<br>30km swath & 6 meters per pixel<br>*Context Imaging for HiRISE, CRISM & MRO Science* | Regional Stratigraphy and Morphology | Key: Moderately High Resolution with Coverage<br>Targeted & Regional Survey<br>High Data Rate |
| **HiRISE** **(High Resolution Imaging Science Experiment)** | High-Resolution Camera (0.5 m aperture) | Color Images, Stereo by Site Revisit<br>*From 300km:* < 1 meter per pixel<br>(Ground sampling @ 0.3 meters per pixel)<br>*Swath*: 6km in RED (broadband)<br>1.2km in Blue-Green & NIR | Stratigraphy, Geologic Processes and Morphology | Key: Very High Resolution<br>Targeted Imaging<br>Very High Data Rate |
| **MARCI** **(Mars Color Imager)** | Wide-Angle Color Imager | Coverage of Atmospheric clouds, hazes & ozone and surface albedo in<br>7 color bands (0.28-0.8 µm)<br>(2 UV, 5 Visible) | Global Weather and Surface Change | Key: Daily Global Coverage<br>Daily Global Mapping,<br>Continuous Dayside Operations<br>Moderate Data Rate |
| **MCS** **(Mars Climate Sounder)** | Atmospheric Sounder | Atmospheric Profiles of Water, Dust, CO2 & Temperature, Polar Radiation Balance<br>0-80km vertical coverage,<br>Vertical Resolution ~ 5km) | Atmospheric Structure, Transport and Polar Processes | Key: Global Limb Sounding<br>Daily Global Limb & Nadir Mapping,<br>Continuous Operations<br>Low Data Rate |
| **SHARAD** **(Shallow Radar)** | Shallow Subsurface RADAR | Ground Penetrating RADAR<br>Transmit Split Band at 20MHz<br>< 1km; 10-20 m Vert. Resolution<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 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
**PI= Principal Investigator; TL = Team Leader**

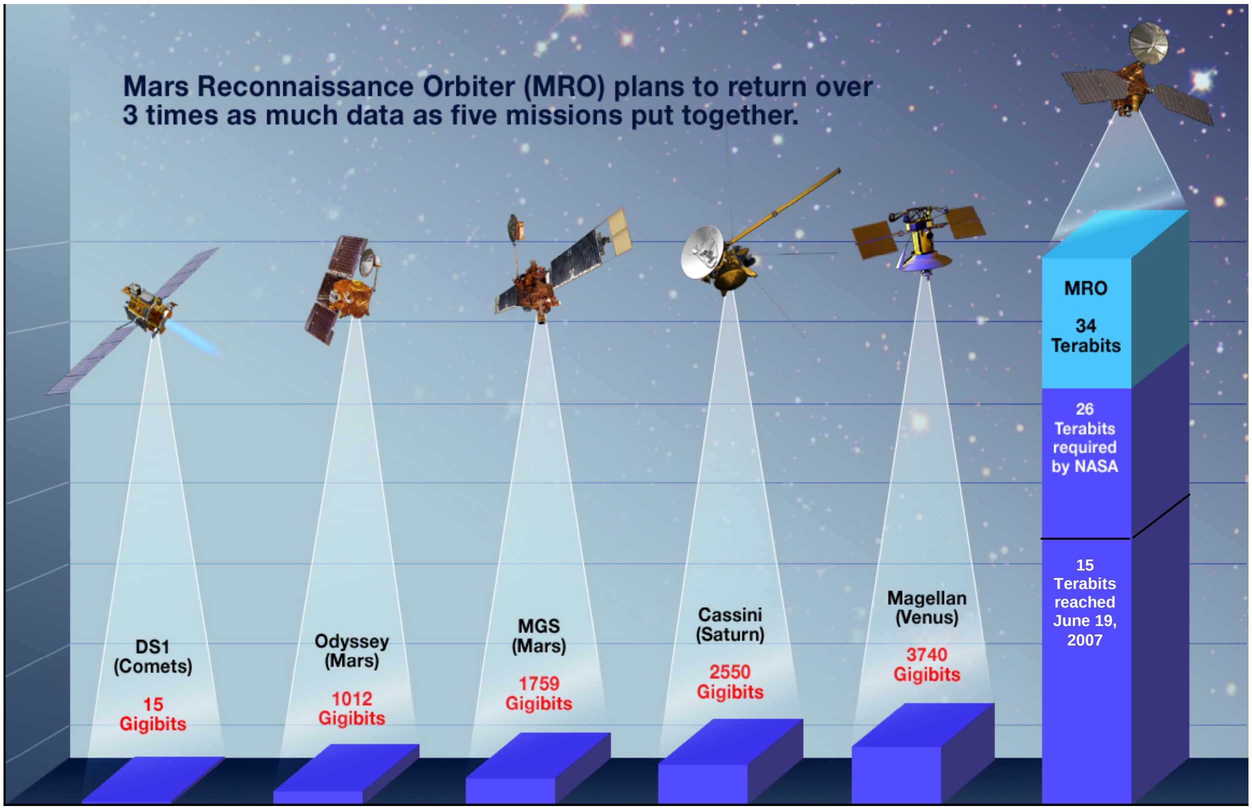

**Figure 1. Data Return Comparison**

MRO will accomplish its science objectives by conducting a program of:

- Global mapping,
- Regional survey, and
- Globally-distributed, targeted science observations for one Mars year, and analysis of the returned data.

MRO is a multi-faceted mission. Exploratory nature requires flexibility in planning, particularly for targeted observations, and requires internal and external coordination to implement diverse NASA Mars Exploration Program (MEP) requirements. MRO instruments are, by design, higher resolution than their predecessors; hence, they return much more data than ever before, and require more uplink planning than previously required (i.e., more targets for more teams and more patching observations into a useful survey pattern). MRO has three major observation modes, which can possibly compete with one another. They are: Global Mapping, Regional Survey, and Targeted Observations. MRO has three targeting instruments, each with their own off-nadir observing requirements, which can also compete with one another. However, coordinated targeting of many sites by more than one instrument is required for site characterization and certification, and stereo imaging is required for science as well as site certification.

The MRO spacecraft telecommunication and computer systems design allows for up to 6 megabits per second (mbps) data rate at closest Mars-to-Earth range. Throughout the PSP, MRO will downlink engineering and science data to Earth from ~500 kilobits per second (Kbps) to ~6 Mbps. With the current (Deep Space Network) DSN schedule, our downlink data volume can nominally go as high as ~34 Terabits for the entire PSP. This is unprecedented for planetary exploration missions. See Fig. 1 for the comparison.

The Phoenix project, a Mars lander mission launching in 2007, will arrive at Mars in May 2008. MRO will play a major support role in the Phoenix Entry, Descend and Landing (EDL) events by recording the EDL data using ELECTRA, the onboard ultra-high frequency (UHF) relay instrument. MRO will provide relay, both forward link and return link support, for the next 90 days of Phoenix primary mission while supporting MRO's own science activities.

## II. Journey to Mars

### A. Launch

MRO was launched from Cape Canaveral, Florida on 12 August 2005 in an Atlas V 401 from Space Launch Complex 41 at 11:43:00 Greenwich Mean Time (GMT). (See Fig. 2). The Atlas booster, in combination with the Centaur upper stage, first delivered the spacecraft into a targeted parking orbit. After a brief coast period, a restart of the Centaur upper stage placed MRO into an interplanetary transfer trajectory. The spacecraft separated over Indonesia and autonomously began its onboard post-separation sequencing which included powering on the telecommunications subsystem. As the spacecraft traversed the Pacific Ocean, it used onboard block-driven commands to successfully deploy its appendages in preparation for attitude acquisition. Approximately two minutes after separation, a Japanese tracking station, Uchinoura 34M station (a unique augmentation to DSN for the MRO mission), acquired frame lock and began flowing data to the Jet Propulsion Laboratory in near real-time. Post-launch reconstruction confirmed that both solar arrays and the High Gain Antenna (HGA) were smoothly and successfully fully deployed. After acquiring inertial reference using one of its two Star-Trackers, the spacecraft successfully slewed to the initial acquisition attitude and transitioned to reaction wheels. Full uplink commandability and two-way tracking was established with the spacecraft as it rose over Goldstone, and a post-launch assessment confirmed that all subsystems were healthy and operating properly.

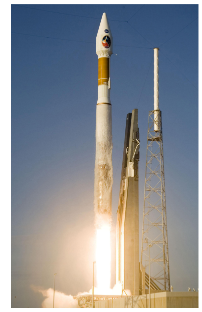

**Figure 2. MRO Launches on August 12, 2005**

### B. Cruise and Approach

Following a successful launch, MRO began its seven-month journey to Mars. During this phase, MRO followed a Type-I ballistic trajectory which was designed to deliver the orbiter on a southern approach trajectory to Mars with the arrival time of 8:30 p.m. LMST. Figure 3 provides a view of the interplanetary trajectory.

To protect critical activities associated with the spacecraft's final approach to Mars, the seven-month cruise was partitioned into two unique and very distinct mission phases. The first five months, the *cruise* phase, included daily monitoring of the orbiter subsystems, navigation activities to determine and correct the vehicle's flight path to Mars, spacecraft subsystem and science payload checkout, and calibrations. Eighteen unique activities were executed during this phase of flight and ranged from calibrating the spacecraft thrusters to in-flight check-out of the science instruments.

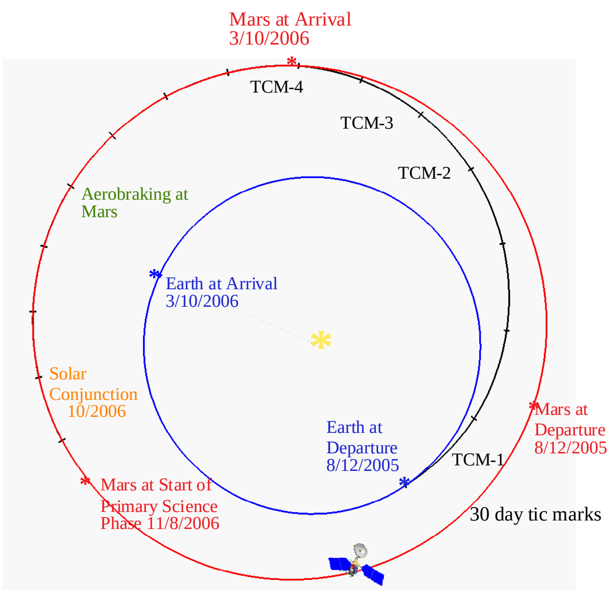


**Figure 3. Interplanetary Trajectory**

The final two months, the *approach* phase, included those activities required to prepare the spacecraft for Mars Orbit Insertion (MOI) and the Optical Navigation Experiment. After the spacecraft had been properly configured for MOI, the Optical Navigation Camera (ONC) was used to observe the Martian moons, Phobos and Deimos, with respect to each other and to the celestial background. This information allowed analysts to accurately determine the location of the orbiter and compare it to the radiometric navigation solution set. ONC was used to demonstrate this technique to provide the capability for future missions to relay on it. MRO's primary approach navigation is ranging, Doppler and Delta Dor measurements.

In order to ensure the success of MOI, the flight team was divided into two subteams. One team was required to ensure the success of day-to-day space flight activities, performing science and engineering calibrations, while the other subteam, consisting of mission manager, spacecraft engineer, system engineers, and subsystem engineers, concentrated on the development, test and training, and risk reduction of MOI. The MOI sequence was built, tested many times and uplinked to the spacecraft prior to the MOI event. Several contingency plans and products were developed, tested and readied for uplink in case the MOI sequence did not go as planned.

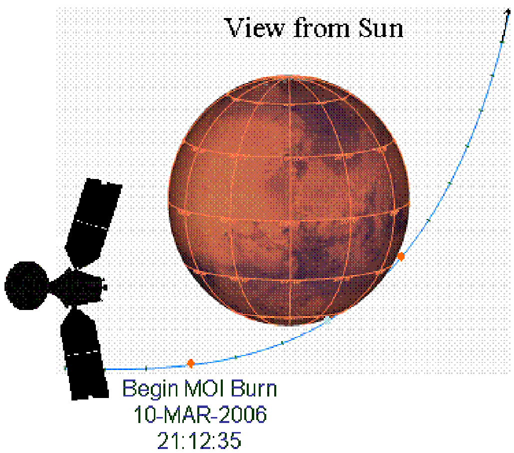

**Figure 4. View from the Sun**

### C. Mars Orbit Insertion

MRO was inserted into Martian orbit at 21:36:00 GMT on March 10, 2006 by executing a propulsive maneuver that allowed the planet's gravitational force to capture the spacecraft into a 35.5 hour orbit. Figure 4 is a view of the insertion burn as seen from the Sun. The 27-minute burn was executed using the thrust from all six main engines in combination with a constant pitch-over maneuver to reduce the finite burn loss. Pitch and yaw control was maintained by off-pulsing the six trajectory correction maneuver (TCM) engines while roll control was provided using the eight ACS (attitude control system) engines. Real-time engineering telemetry was available at 160 bps throughout the burn until the spacecraft was occulted by Mars, approximately 21 minutes into the burn. Although the 1000.4 m/s burn terminated behind the planet, onboard sequencing successfully reconfigured the orbiter for reacquisition by the earth which occurred at approximately 22:16:00 GMT. With the aid of two-way tracking, the navigation team determined that the spacecraft had been successfully captured into the predicted 35.5 hour orbit with a periapsis altitude of 425 km.

### D. Aerobraking and Transition

The aerobraking mission phase began on March 23, 2006 and concluded in late summer, prior to transition to the PSP. During this phase, the spacecraft dropped into the upper portions of the Martian atmosphere and used the resulting aerodynamic drag to remove kinetic energy from the spacecraft's orbit. As kinetic energy is removed, the spacecraft's highly-elliptical 35-hour orbit is modified into a near-circular, 2-hour orbit. In addition to the reduced period, the execution of each "drag pass" is carefully phased with the precession of the orbital elements such that the orientation of the ascending node is modified from its capture value of 8:30 pm to the preferred value of 3:00 pm. The amount of delta-v removed on each drag-pass is regulated by controlling the spacecraft altitude through a series of aerobraking burn maneuvers (ABMs). Figure 5 is an illustrated view of the aerobraking process.

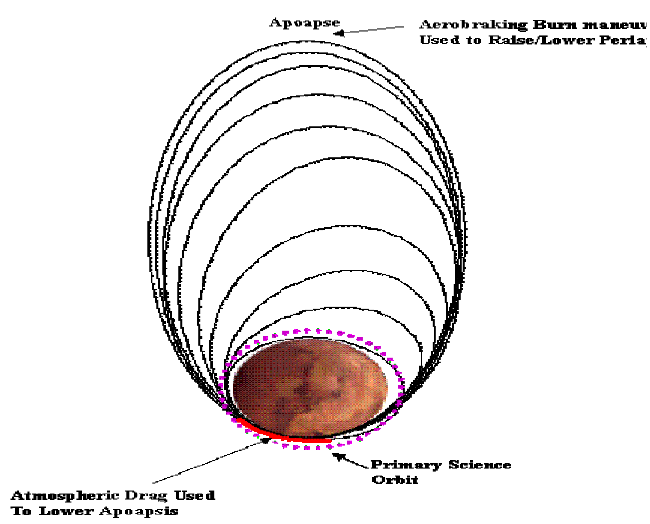

**Figure 5. Aerobraking Burn Maneuvers (ABM)**

The aerobraking termination maneuver (ABX) was conducted on August 31, 2006, concluding a little over five months of aerobraking phase, and reached the value of 3:10 pm for the ascending node. Unfortunately, during the aerobraking period the Ka exciter, as part of the SDST, failed on May 26, 2006. The anomaly investigation identified the probable root cause to be the failure of the amplifier, and thus the future Ka experiment was hampered. Near the end of the aerobraking phase, the wave guide transfer switch failed. As MRO went through the aerobraking drag passes, it was switched from HGA to LGA in order to maintain contact with the earth for as long as the spacecraft was not occulted. On August 16, 2006, the WTS #1 switch failure was detected, which led the team to use only HGA as the communication mechanism for the remaining of the aerobraking phase.

Transition was the last in a series of phases designed to deliver MRO into its final science orbit. Over a two-week period, two propulsive maneuvers were used to place the orbiter in a near-circular, sun-synchronous orbit with periapsis frozen over the Martian South Pole. Given the final orbit of 255 km x 320 km, the MRO spacecraft then underwent a series of final checkouts prior to commencing primary science operations in November of 2006. See Fig. 6 for detail of the schedule.

Designing and implementing a phase heavily filled with unique activities right after the critical period of aerobraking created difficulties in workload balance. Operations support for aerobraking was conducted around the clock, seven days a week, and finding a way to divide the already thin flight teams into four subteams became a challenging task.

Similarly to MOI preparation, a separate team was formed with mission manager, spacecraft engineer, system engineers, payload operations engineers, and navigators, to plan and prepare the details of the transition activities. This team defined the activities involved for each instrument and for the spacecraft, and identified the complexities, requirements, implementation and execution schedule. After consultation with each team chief to negotiate team resources and testbed resources, the schedule was presented to management for approval. Because of resource sharing, the entire development period of the transition phase was in parallel with the aerobraking phase.

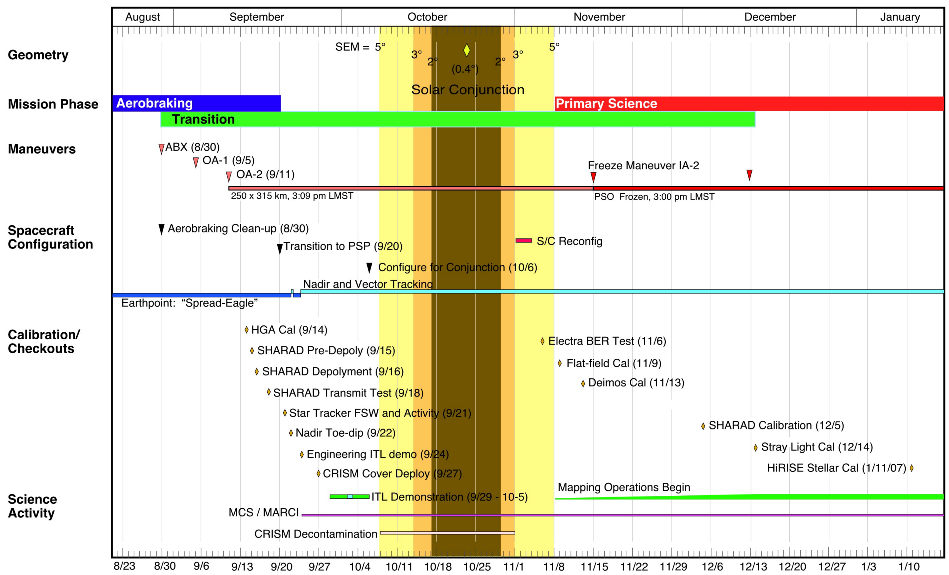


**Figure 6. Transition Phase Activities**

## III. Science Planning

The following section outlines the design various aspects which have been planned to streamline the complicated science planning process.

### A. Onboard Capabilities

The MRO spacecraft is designed to support targeting with off-nadir rolls, up to 30˚ in roll angle, for as many as 4 different targets per orbit. Onboard logic uses the latest ephemeris and an Integrated Target List (ITL) to perform either sequentially or concurrently observations. An ITL is a list of targets on Mars, designated by latitude, longitude and expected activity center time, derived from the final list of targets (the final output of the science planning process will be described later), and gets uplinked to the spacecraft. The spacecraft will use the current onboard Mars ephemeris file to compute the time of target over-flight and initiate a series of onboard command blocks to execute the spacecraft and instrument sequences. Timing updates due to navigation orbit prediction updates are handled by updating the spacecraft ephemeris only.

### B. Navigation Strategy

The MRO mission is designed to provide a PSO that 1) optimizes a mix of observation modes and 2) simplifies operations. The PSO is a frozen (nearly) circular orbit: 255 km (at 90S) to 320 km (at 90N), which simplifies operations planning and provides more systematic coverage. A low altitude enhances spatial resolution while still achieving targeting precision. Nearly every location on the planet can be viewed at least once (and usually twice) every 17 days with less than a 20˚ spacecraft roll, which means there are multiple opportunities on a monthly basis to target specific sites.

The PSO is designed to repeat on a short-term basis to provide global access and repeated targeting opportunities, as well as to provide long-term global coverage of Mars with ground track spacing of less than 5 km. The orbit control strategy is expected to maintain this fine spacing to less than 2 km. This is done through execution of orbit trim maneuvers (OTMs) which are typically very small burns (< 2m/s). Because of the high resolution of some of the MRO instruments, the MRO point accuracy requirement is stringent. The prediction uncertainty may cause the target to be invalid from the onboard flight software (FSW) perspective. Figure 7, shows a plot of the predicted pointing angle uncertainties versus days since Orbit Determination (OD) cutoff. This illustrates the error in the Navigation orbit prediction expected over 7 weeks.

### C. Planning Challenges

Unlike previous Mars orbiters, MRO has special planning challenges for its primary science phase because of the conflicting needs to routinely target off of nadir and to take nadir observations. The 17-day repeat cycle allows for the retake of a critical opportunity within the next cycle, which assists with the science planning process. Since MRO uses a 2-week execution cycle for the routine telecom management and other spacecraft resource management such as desat and HGA management, providing the same planning process for a 14-day science execution cycle becomes necessary. The 14-day science execution cycle includes up to 280 conflict-free targeted off-nadir interactive observations (based on 20 per day x 14 days) for the three science instruments taking Interactive Observations (IOs), with roll angles up to plus/minus 30° about the X-axis. The IO selection process also includes targets to support MEP for future landed assets.

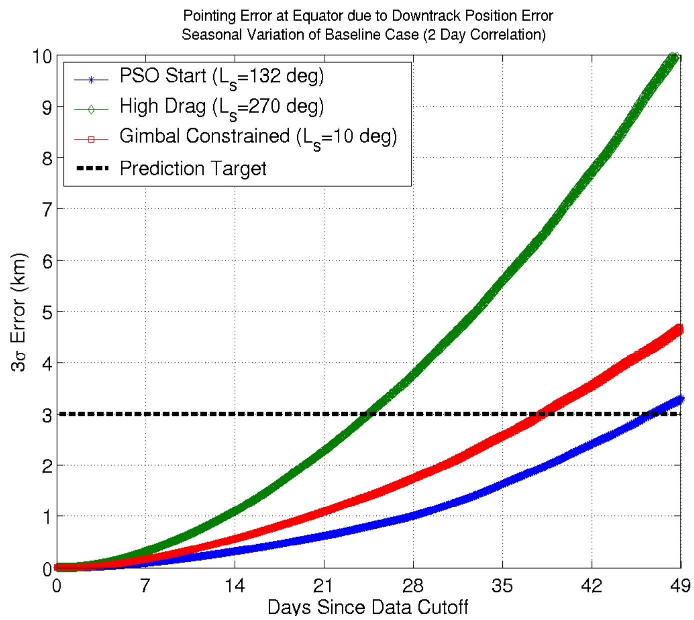


**Figure 7. Predicted Pointing angle uncertainties**

IOs have an interactive nature in that one instrument's activity can affect other science instruments and the spacecraft. For example, one off-nadir target from HiRISE will cause the spacecraft to roll off nadir, and depending on the size of the role, it could result in no observation from MCS during that period. Therefore each IO needs to be planned on a collaborative basis through the IO planning process based on the rules carefully defined by the Target Acquisition Group (TAG). Observations that do not change or control spacecraft operations or the operations of other instruments are called Non-Interactive Observations (NIOs). By definition these are all nadir observations.

The overall science planning process must account for the appropriate navigation prediction uncertainty when identifying potential targets that fall within the spacecraft roll capability. The long navigation predicts are produced at the beginning of the 2-week planning cycle which covers the 2-week execution cycle. Because only the timing information is required for the nadir observations, and because of the uncertainty of the predicted ephemeris, and the uncertainty in upcoming ground-tracks, NIOs are generally planned weekly.

In support of the onboard ephemeris and science NIO planning process, the Navigation team provides a two-week, short-term orbit prediction, at a minimum of two times per week, in order to meet the required prediction accuracies. Depending on the season and atmosphere predictability, the updates may occur as frequently as every day. Navigation needs to satisfy the 3σ short-term orbiter position requirements for the downtrack, crosstrack, and radial uncertainties of 1.5 km, 0.05 km, and 0.04 km, respectively. The short-term ephemeris will also be used to generate the onboard spacecraft ephemeris file and to support the non-interactive science planning process.

### D. Planning Processes

The Project Science Group (PSG) normally meets quarterly, and consists of Principle Investigators (PI), Team Leads (TL), the Project Scientist and the Deputy Scientist. The objective of these meetings is to discuss possible changes to planning rules, allocations, and priorities, and to make decisions on major observation campaigns (e.g. landing site characterization). Examples of science planning rules are:

- MCS rules: limit the number of large (>9°) off-nadir slews and their distribution (e.g. in adjacent orbits).
- CRISM rules: reserve a certain number of exclusion zones (orbit segments) for nadir survey observations. (In early PSP, every other orbit is a No-Slew Zone.)
- SHARAD rules: provide priority in observing conflicts on the night side. (Others have priority on the dayside, except in scheduled SHARAD exclusion zones.)

TAG, a subgroup of the PSG, was established to guide science planning, and members include the PI and TLs from the investigations which are taking data during the Primary Science Phase; an Electra representative during the PSP relay; MRO Project Scientist, Deputy Project Scientist, NASA MRO Program Scientist, and augmented by 1-2 MEP representatives supporting landing site studies and/or relay activities.

In order to stay within the timeline and reduce cost, mission operations are designed to evolve existing Mars Mission approaches. For example, the entire mission operation is designed to retain a distributed science experiment operations approach. The MRO project provides required tools for uplink processing, targeting and data tracking, provide a forum (i.e., TAG meeting) for coordinating strategic observation planning, provide the ability to coordinate and validate interactive observations while preserving non-interactive planning, provide a process that resolves conflicts based on agreed rules and priorities, and retain ability for science investigations to plan their observations within defined data allocations. TAG meetings are held every other Monday during the week that IOs are scheduled. These TAG meetings:

- schedule “must-have” observations (including selected MEP targets and relay opportunities); allowing for specific individual science must-haves;
- schedule Exclusion Zones for CRISM Atmospheric and Multi-Spectral Surveys; and
- schedule Exclusion Zones for SHARAD Polar Survey;

After the TAG meeting, each science team provides their requests to the Payload Operations Support Team (POST). A special process (Triple Play) was devised to schedule stereo images, coordinated targets and individual team observations (in priority order). A round-robin method is used in each category. The IO planning process produces an Integrated Payload Target File (IPTF) at the end of the first week of the two-week IO planning cycle. Non-interactive observations (NIOs), are merged with the planned IOs into an IPTF, and sent to the Flight Engineering team, where they convert the IPTF into an ITL for uplink to the spacecraft. It is common for the combined number of IOs and NIOs to exceed 500 targets per week. As the mission moves forward, changes and improvements are made to the science planning process to improve efficiency and reduce the workload of each science team.

## IV. Relay

In addition to returning many terabits of scientific data, MRO is also one of the key relay assets for the Mars Exploration Program. The first of such assets that MRO will support is the Phoenix project. Phoenix will be launched on August 4, 2007 on a Delta II rocket, landing on Mars in May of 2008. MRO will provide three kinds of support to Phoenix. The first was the landing site selection using MRO’s high resolution instruments to take data in the landing ellipse. With the help of MRO’s images of the Mars surface using the HiRISE, CRISM and CTX instruments, Phoenix was able to select its primary landing site. MRO’s second objective is to support the EDL operations by taking opening-loop recording data using MRO’s onboard UHF antenna, Electra. This data will be used to help Phoenix team determine the trajectory and location of the spacecraft. In order to properly support EDL, MRO will perform phasing maneuvers to get the spacecraft to the orbit at which it can see the Phoenix spacecraft as it approaches Mars. Currently, at L-54 days, MRO will receive trajectory information from Phoenix which documents its landing site ellipse, with potential tweaks at L-13 days. Lastly, Electra will provide daily data relay function for Phoenix, by conducting the relay in the close-loop form such that there is a special handshake between sender and receiver. Data will be retransmitted from the lander to MRO if there is data drop-out. The duration of contact between MRO and Phoenix ranges from 5 minutes to 15 minutes depending on the elevation angle.

Relay customers (landed assets) will be treated essentially as a science instrument during the science planning process. A Memorandum of Agreement (MOA) has been established with the Phoenix project. During MRO’s primary science phase. MRO will provide support for up to two over-flight relay opportunities per sol. The Phoenix project will provide their inputs to the TAG meeting as part of the must-haves, and an exclusion zone will be identified for each of the opportunities in order to ensure that no other conflicting events will take place. The relay opportunity will be used for both forward and return link.

## V. Data Systems

### A. Solid State Recorder

A solid-state recorder (SSR) with a 100 gigabit (Gbit) end-of-mission storage capability (160 Gbit beginning of life) is provided to handle this large data volume. The SSR is divided into two areas of memory, one for the storage of the raw science data produced by the instruments, and the second for the storage of AOS framed data awaiting downlink.

To provide operational independence among the instruments, dedicated hard partitions are provided for each instrument for the storage of raw science data generated with each observation. Each instrument's interface software will control the writing of its raw partition, and the spacecraft FSW is responsible for read-out of instrument data from the raw partition to the processing buffer. The framed data area of the SSR is thus configured as one large hard partition for X-band (and another for Ka-band downlink before the Ka failure), which is subdivided into smaller soft partitions by instruments and managed by the FSW. Soft partition is managed based on the PSG agreement in terms of instrument data volume allocation.

### B. Data Flow

After an instrument finishes its data take, the raw data is written to the raw SSR partition associated with that specific instrument by the instrument onboard software. Spacecraft science interface software produces science data products by reading from the raw partition. This data is passed first to the product telemetry software which creates CCSDS File Delivery Protocol (CFDP) products out of it. Specifically it creates an Metadata Product Delivery Unit (MPDU) followed by however many Data Product Delivery Units (DPDUs) are necessary to complete the product, and then finally another MPDU. This final MPDU is also duplicated in a special Application ID (APID) that is routed through the engineering packet buffer downlink path so that it is radiated to the ground and routed from the DSN to JPL at a higher priority than the rest of the product. MRO uses CFDP to manage the large data volume, and CFDP files systems allow us to associate the downlink files with uplink requests.

After being configured into a product, the science data is packetized, framed, and sent to a pre-SSR framed data buffer for eventual storage in an SSR soft partition. The FSW will control the writing of the instrument's framed data based on agreed-to bandwidth percentages. If an instrument generates more data for transfer to one of these framed buffers in the SSR than its allocation allows, the FSW will pause that instrument from being able to write additional data until space has been freed up via the reading of data out of the framed buffer for downlink. MRO uses Advanced Orbiting System (AOS) transfer frames to manage the large data volume. The AOS frames give us much larger field to uniquely identify each frame in the telemetry frame. MRO is the first planet mission which uses AOS and CFDP.

A set of 9 Virtual Channels (VCs) have been defined to manage the downlink of data off of the spacecraft. The grouping of these 9 VCs are also used for the prioritization of data return from DSN stations to JPL. VC0 contains realtime engineering data and MCS data when in DSN contact; VC1 and VC2 contain unused data which will be returned in real-time from the DSN to JPL; VC3 contains MCS data; VC4, recorded engineering; VC5 contains Electra relay data which is returned from the station to JPL as the second highest priority; VC6, X band science; VC7 contains Ka band science data; and VC8, which contains unknown and overflow data which will be returned from the DSN to JPL in a "store and forward" manner after the pass. In addition, VC63 data, containing fill frames, will not be shipped to JPL.

Much of the data management process outlined above is configurable via a set of FSW configuration files. Hard partition updates will result in the loss of all data not yet transmitted off the spacecraft. However, the design of the soft partitions for framed data does allow for resizing these buffers without losing any data in the raw partitions. This design also allows for updates to the instrument allocation percentages within the X-band and Ka-Band framed buffers without losing any data at all

### C. DSN Upgrades

MRO pushes the limits of three of NASA's DSN facilities due to its high data rate and large data volume. Prior deep space missions have returned data at a much lower rate. The following items are the major upgrades that DSN provided for the MRO project:

1. upgrade of several subsystems in order to improve the Radio Science (RS) encoded data processing performance from 3 mbps to 6 mbps;

2. upgrade subsystems to handle up to 1.6 mbps turbo encoded data;
3. upgrade the data storage system to increase temporary data storage in case of data outage;
4. increase the bandwidth between DSN stations and JPL to allow for 24 hours of one 8-hour track data delivery;
5. provide a frame accountability system to allow for fast data re-transmission request generation and uplink.

### D. CFDP Processing

Once the data arrives at JPL, it will go through JPL's multimission telemetry processing system, i.e., frame sync, packet extraction etc. Once the DPDU is extracted, the CFDP processor will take over the processing. A CFDP file will be formed once a DPDU is received. The file will continuously grow as long as more DPDU are received.

Several trigger points are set in order to push out the files to users. They are used in combination to satisfy different users requests. For example, MRO's largest data product is from the HiRISE instrument. The high resolution images can get as large as 28 Gbits, which frequently span over multiple DSN tracks. The significant triggers are:

1. end-of-file PDU and a complete file. It is important to understand that these two items must be combined. In the case of a 28 Gbits HiRISE image, the reaching of the end-of-file PDU does not mean the file is completed because the end-of-file PDU may be coming from the second station at the earliest tracking time, and the rest of the data is still being transmitted from a previous track at another station.
2. an inactivity timer which will set at, for example, 72 hours after track. If data has not shown up in the data system after 72 hours, the probability of its appearance is very low.
3. a third kind of timer which is set such that the file will be produced periodically, for example, once every N hours. This trigger will let the users a know that the data is being received and processed as planned.

### E. Data Accountability

The systems described above are very capable, allowing planning flexibility and providing a great data return. However, this flexibility has its cost. Because of the ephemeris prediction accuracy requirements, we may have planned observations that, when execution time comes, violate the flight rules, such as > 30˚ in roll angle. We may also have squeezed in more observations than allowed, resulting in lost data. MRO employs an end-to-end data accountability system to help users identify the location of their data. Starting from the planning cycle, the products prediction system takes the planning results as inputs, updating throughout the execution cycle, and providing the science team with up-to-date expected product lists for each instrument. Status telemetries are generated as the command files are uploaded to the spacecraft, processed by FSW and instruments. Status telemetry are also generated as the data products are formed, processed through FSW and SSR, and downlinked to Earth. The data accountability system correlates the predicted product and its status as it traverses through the spacecraft data system and ground data system, and provides correlated information to the science users similar to tracking systems used by many commercial transportation companies.

In addition to product accountability there is frame accountability. Although robust and capable of delivering to MRO a very high data rate, weather conditions and margin management can and has caused data dropout in the RF system. Late lock-up due to procedure error or hardware failure can cause frame loss as well. One of the capabilities which DSN has upgraded for MRO is a frame accounting system at the station. Before the data is sent back to JPL, the accounting information arrives at JPL much earlier which allows the project to react. Re-transmission capability is designed for MRO to handle data dropout, and in order for JPL to use the re-transmission capability effectively, the fast frame accountability report, fast command generation and radiation are all essential. Based on the frame accountability report, gaps in the data stream will be identified. The software will generate command sets based on the gaps, the spacecraft commanding timing, and a set of user-specified criteria. Because MRO has weekly almost-continuous DSN coverage, a schedule command radiation can happen very frequently. As long as the onboard data has not yet been overwritten, data can be downlinked. Out of more than 60,000 products delivered to date, an average of 93% of the data has been completed.

The CFDP process is designed as an add-only process. In other words, if there are gaps in the file, and there is additional data retransmitted from the spacecraft to the ground, those data, in units of PDU, will be added to the existing file as long as the file is not marked complete. CFDP generates more than just the data files, it generates transaction log files as well, which describe the quality of the data and other ancillary information, and is in a one-to-one relationship with the data file.

### F. Data Distribution

Once a set of files (consisting of the raw science data file and the transaction log file) are published by the CFDP processor, they are ready for distribution. A multi-mission data distribution system is adapted to meet MRO's needs. The Raw Science Data Server (RSDS) uses a database to maintain a catalog of all files, and maintains user id and password for security purposes. The system not only allows users to interactively retrieve their files, but also provides APIs for users to automate their processes. In addition, a user can go into the system to subscribe based on the type of file. Once a new file of that type arrives, the file will be pushed to the user's system.

RSDS is supported by multiple-dedicated T1 lines connected between JPL and different instrument sites, specifically, the University of Arizona (Tucson), Applied Physics Lab (John Hopkins University), and Malin Space Science Systems (San Diego). These dedicated T1 lines are sized to allow for twice the highest daily data volume that a site will receive, and has very stringent MTBF and MTTR. Users can also use internet/internet2 to access RSDS.

## VI. Implementation 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 Space Systems Company 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, Kennedy Space Center selected the Lockheed-Martin Astronautics Atlas V 401 as the launch vehicle for the MRO mission.

The system-level Preliminary Design Review (PDR) was accomplished in July 2002 with the formal NASA confirmation of MRO given in September 2002. MRO successfully completed its system-level Critical Design Review (CDR) in May 2003, followed by the successful Assembly, Test, and Launch Operations (ATLO) Readiness Review in March 2004 and subsequent ATLO activities. MRO was launched on August 12, 2005 with science data acquisition commencing in November $8^{th}$, 2006, once the MRO spacecraft had reached its primary science orbit. Science operations will be conducted for at least one Martian year (approximately two Earth years). As of June 2007, MRO has returned more than 15 Terabits worth of science data, thus meeting one of its minimum success criteria.

Immediately after the science phase, the MRO spacecraft will begin its relay phase. This phase will continue until the planned end of mission on December 31, 2010. Attitude control propellant was loaded on the vehicle in the case that a mission extension is desired, so the vehicle could continue to function as a relay spacecraft with the Electra payload until the year 2015.

## VII. Conclusion

MRO is a major 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.

## Acknowledgments

The authors thank Mrs. Janis Capraro for her assistance in the preparation of this manuscript. The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

## References

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

[2] M. D. (Dan) Johnston, James E. Graf, Richard W. Zurek, Howard J. Eisen, Benhan Jai, "The Mars Reconnaissance Orbiter Mission: From Launch to the Primary Science Orbit", *Proceedings of the IEEE Aerospace Conference, March 2007*