

The Mars Reconnaissance Orbiter Mission Operations: Architecture and Approach

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ABSTRACT

The Mars Reconnaissance Orbiter (MRO) was launched on August 12, 2005 by an Atlas V launch vehicle from Cape Canaveral Air Force Station. MRO will carry a rich set of science instruments to Mars and provide global, regional survey, and targeted observations. In addition, a set of engineering instruments providing optical navigation, Ka band telecommunication and UHF relay services to future Mars missions are part of the MRO payload.

During the mission, the MRO operations teams are 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 (> 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/allocation process. This paper describes what MRO project is implementing to solve these challenges.

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1.0 INTRODUCTION

The MRO orbiter was launched, from Cape Canaveral, Florida, using a Lockheed Martin Atlas V-401 launch vehicle on August 12, 2005.

The transit time to Mars will be approximately seven months. During this period, a series of trajectory course corrections will be carried out. The orbiter payload will be checked out and a series of instrument and spacecraft calibrations performed.

After arriving at Mars in March 2006, the MRO orbiter will be propulsively inserted into a highly elliptical capture orbit with a period of 35 hours. The orbiter will use aerobraking techniques to reduce its orbit to near that needed for science observations.

The 255 x 320 km Primary Science Orbit (PSO) will be a near-polar orbit with periapsis frozen over the South Pole. It will be sun-synchronous with an ascending node orientation that provides a Local Mean Solar Time (LMST) of 3:00 p.m. at the equator. The SHARAD antenna and the CRISM cover will be deployed, the instruments will be checked out and any remaining calibrations will be performed before the Primary Science Phase (PSP) begins.

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, 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.

Please see Table 1 for the complete listing of science instruments on board the MRO spacecraft.

Table 1. Science Investigation Objectives

<i>Instrument</i>	<i>Type</i>	<i>Measurement Objectives</i>	<i>Science Goals</i>	<i>Attributes</i>
CRISM	High-Resolution Imaging Spectrometer	Hyper-spectral Image Cubes 514 spectral bands, 0.4-4 microns, 7 nm res. <i>From 300km:</i> 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 <i>From 300km altitude:</i> 30km swath & 6m/pixel <i>Context Imaging for HiRISE/CRISM & MRO Science</i>	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 <i>From 300km:</i> < 1 m/pixel (Ground sampling @ 0.3 m/pixel) <i>Swath:</i> 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 μ m) (2 UV, 5 Visible)	Global Weather and Surface Change	Key: Daily Global Coverage Daily Global Mapping, Continuous Dayside Operations Moderate Data Rate
MCS	Atmospheric Sounder	Atmospheric Profiles of Water, Dust, CO ₂ & Temperature Polar Radiation Balance 0-80km vertical coverage Vertical Resolution ~ 5km)	Atmospheric Structure, Transport and Polar Processes	Key: Global Limb Sounding Daily Global Limb & Nadir Mapping, Continuous Operations 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			

The 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 by 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 Mars Exploration Program requirements. MRO instruments are, by design, higher resolution than their predecessors; hence, returning much more data than before, and requiring more uplink planning than before (i.e., more targets for more teams and patching observations into a useful survey pattern). MRO has three major observation modes, which can be in conflict with one another, they are Global Mapping, Regional Survey, and Targeted Observations. MRO has 3 targeting instruments, each with their own off-nadir observing requirements and possibly competing desires. 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 allow for up to 6 megabits per second (Mbps) data rate (combination of X and Ka band) at closest Mars to Earth range. Throughout the PSP, the MRO will downlink engineering and science data to Earth from ~500Kbps to ~6 Mbps. With 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 the planetary exploration missions. Please see figure 1 for the comparison.

2.0 SCIENCE PLANNING

Many aspects of the design have been thought out to help streamline the complicated science planning process

2.1 On-Board 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 reduce observing errors for multiple targets, which minimizes the need for late updates by multiple teams

Figure 1

This capability allows the scientists to generate a simple list of targets on Mars, designated by latitude and longitude, which gets uplinked to the spacecraft. The spacecraft will use the current on-board Mars ephemeris file to compute the time of target over-flight and initiate a series of on-board command blocks to execute the spacecraft and instrument sequences. Timing updates due to navigation orbit prediction updates are handled by simply updating the spacecraft ephemeris only.

2.2 Navigation Strategy

The MRO mission is designed to provide a Primary Science Orbit (PSO) that optimizes a mix of observation modes and 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. Altitude enhances spatial resolution while not being so low that targeting precision is not achieved. Nearly every place on the planet can be viewed at least once (and usually twice) every 17 days with less than a 20° spacecraft roll, which means multiple opportunities on a monthly basis to target specific sites.

The Primary Science Orbit (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 will typically be very small burns (< 2m/s).

2.2 Planning Challenges

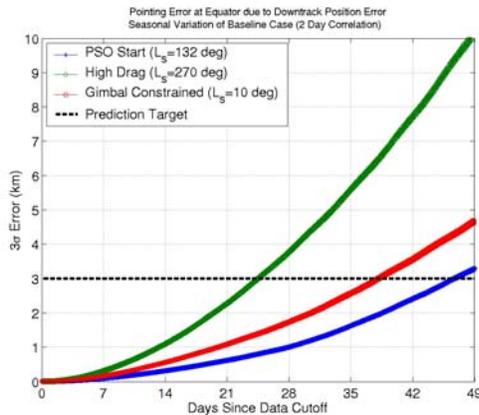
Unlike previous Mars orbiters, MRO has special planning challenges for its primary science phase due to the need to routinely target off of nadir. A robust science planning design must provide the same planning process for a 14 day science execution cycle, including up to 280 conflict-free targeted off-nadir interactive observations (based on 20 per day x 14 days) for the 3 science instruments taking Interactive Observations

(IOs), with roll angles up to plus/minus 30° about the X-axis. The IO selection process must also include targets to support the Mars Exploration Program (MEP) for future landed assets.

Interactive Observations (IO) are not stand-alone S/C or science activities. Therefore each such IO needs to be planned on a collaborative basis by the Target Acquisition Group (TAG) through the IO planning process.

The overall science planning process must account for the appropriate prediction uncertainty when identifying potential targets that fall within the spacecraft roll capability. Figure 2, a plot of the predicted pointing angle uncertainties vs. days since Orbit Determination (OD) cutoff, illustrates the error in the Navigation orbit prediction expected over 7 weeks.

Figure 2



Observations that do not change or control spacecraft operations or the operations of other instruments are called Non-Interactive Observations (NIOs). These are all, by definition, nadir observations. Due to the uncertainty of the predicted ephemeris, and therefore the uncertainty in upcoming ground-tracks, NIOs will generally be planned weekly.

Non-interactive observations (NIOs), are merged with the planned weekly IOs into an Integrated Payload Target File (IPTF), and sent to the S/C team, where they convert the IPTF into an integrated target list (ITL) for uplink to the S/C.

In support of the on-board ephemeris and science NIO planning process, Navigation will provide a two-week short-term orbit prediction, at minimum, three times per week to meet the required prediction accuracies. Depending on the season and atmosphere predictability,

the updates may be as frequent 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, 0.05km, and 0.04km, respectively. The short-term ephemeris will also be used to generate the on-board spacecraft ephemeris file and to support the non-interactive science planning process.

2.3 Planning Processes

The Targeting Acquisition Group (TAG) is established to guide the science planning. The TAG is a subgroup of the MRO Project Science Group (PSG). The members include PI/TLs of Investigations taking data during Primary Science Phase; an Electra representative during PSP relay; MRO Project Scientist, Deputy Project Scientist, NASA MRO Program Scientist, and augmented by 1-2 MEP representatives (is this true??) supporting landing site studies and/or relay activities

In order to make this work with in the timeline, without re-inventing the wheel, mission operations are designed to evolve existing Mars Mission approaches to meet MRO needs. For example, the MOS is designed to retain a distributed science experiment commanding and data processing approach, provide required tools for targeting and data tracking, provide a forum (i.e., TAG) 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. Any changes to planning rules, allocations, and priorities would be discussed and decided at quarterly PSG meetings. Figure 3 shows the process flow of the bi-weekly IO planning cycle. IO planning procedures are shown in yellow and green boxes.

2.4 PSG

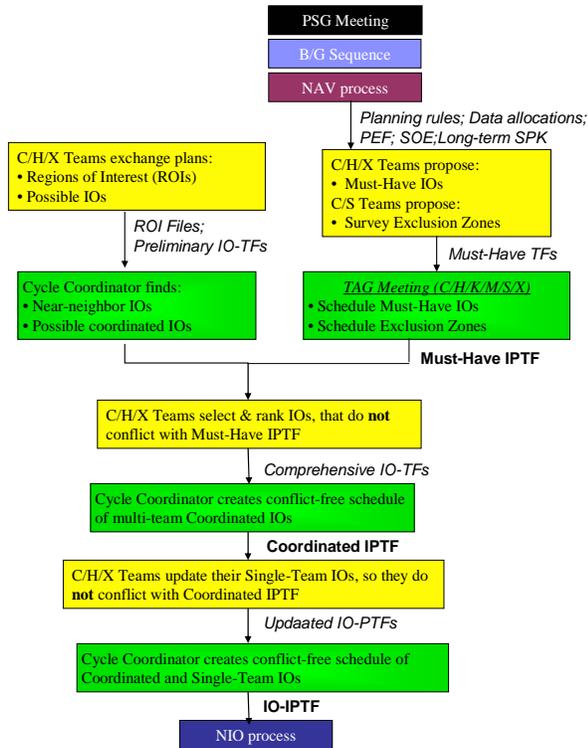
The PSG will meet quarterly to modify, if necessary, science planning rules and data allocations and to make decisions on major observation campaigns (e.g. landing site characterization).

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 nightside. Others have priority on

the dayside, except in scheduled SHARAD exclusion zones.

Figure 3



2.5 Inter-Team Target Coordination

Each 14-day cycle, in the 2-3 working days before the TAG Meeting, CRISM, HiRISE, and CTX (C/H/X) Teams exchange planning data about areas they plan to image in the upcoming cycle. They exchange Region-of-Interest (ROI) Files and Payload Target Files (PTFs), which are processed by the Cycle Coordinator to find likely points on Mars where multi-team coordinated observation could be made.

2.6 TAG Meetings

TAG meetings will be held every other Tuesday, during the week that IOs are scheduled. Each month one week after the S/C background-planning sequence begins, a comprehensive TAG meeting is held where each investigation is represented either in person or via telecon.

These TAG meetings:

- Schedule “Must-Have” observations (incl. selected MEP targets and Relay opportunities);
- Schedule Exclusion Zones for CRISM Atmospheric and Multi-Spectral Surveys;
- Schedule Exclusion Zones for SHARAD Polar Survey; and
- Select Target locations for Must-Have observations in the cycle after next.

2.8 IO Scheduling

After the TAG Meeting, the C/H/X Teams submit PTFs that are ranked-lists of all their desired Interactive Observations. The Cycle Coordinator processes these to find all the Coordinated IOs. The C/H/X Teams can further modify this in a Coordination Telecon on Thursday. Follow-up submissions of PTFs on Friday, allow these teams to schedule all their non-coordinated IOs. A conflict-free Integrated PTF (IPTF) of IOs is generated by the end of the week.

2.9 NIO Scheduling

A Non-Interactive Observation (NIO) is any instrument observation, which does not affect the operation of the spacecraft or any other instrument. Before any NIOs can be planned, it is first necessary to know what IOs have been planned and when. Thus, the Science Teams add NIOs on an ongoing basis (weekly). Characteristics of NIOs are:

- They require the S/C to be nadir pointed (off nadir slews are interactive)
- They are defined by Mars latitude and by orbit (i.e., time).

Figure 4 below shows the planning flow for NIOs (in the yellow and green boxes). The CRISM, HiRISE, SHARAD and CTX science teams have developed a process, whereby they can coordinate NIOs. This is a three-step process, as illustrated in the figure.

2.10 ITL

The uplinked ITL file is a time ordered listing of observations, containing both nadir and off-nadir targets, specified by target latitude (areodetic coordinate frame) and longitude. Additionally, an altitude bias can be input to target different terrain types, like mountains, craters walls or valleys. It is generated from the Final IPTF emerging from the NIO process.

The ITL contains an observation type parameter, which is used to designate the type of observation to be executed.

Figure 4

The spacecraft will use the current on-board Mars ephemeris file to compute the time of target over-flight and initiate a series of on-board command blocks to execute the spacecraft and instrument sequences. Timing updates due to navigation orbit prediction updates are handled by simply updating the spacecraft ephemeris only.

3.0 ON BOARD DATA SYSTEM

3.1 Solid State Recorder

A solid-state recorder (SSR) with a 100 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 framed data awaiting downlink.

To provide operational independence amongst 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. The S/C 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), which is subdivided into smaller soft partitions and managed by the FSW.

3.2 Data Flow

Science interface software produces science data by reading from the raw partition. This data is passed first to the product telemetry software which creates CFDP (CCSDS File Delivery Protocol) products out of it. Specifically it creates an MPDU (Metadata Product Delivery Unit) followed by however many DPDU's (Data Product Delivery Units) are necessary to complete the product and then finally another MPDU. This final MPDU is also duplicated in a special 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. The MRO uses CCSDS File Delivery Protocol (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, then framed, and then 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 reading of data out of the framed buffer for downlink. The 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.

A set of 9 VCs have been defined to manage the downlink of data off of the spacecraft. VC0, VC1 and VC2 data will be returned in real-time from the DSN to JPL. VC3, VC4, VC5, VC6, VC7 and VC8 data will be returned from the DSN to JPL in a store and forward manner after the pass. VC9 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.

4.0 GROUND DATA SYSTEM

4.1 DSN Upgrades

The MRO pushes the limits of three NASA's Deep Space Network (DSN) facilities with its large data rate and data volume. The following items are the major upgrades DSN is providing for the MRO project.

1. Upgrade several subsystems to improve the 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 data storage system to increase temporary data storage in case of data outage
4. Increase bandwidth between DSN stations and JPL to allow for 24 hours of one 8-hour track data delivery.
5. Provide frame accountability system to allow for fast data re-transmission request generation and uplink.

4.2 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, the largest data product of the MRO is from HiRISE instrument. The high resolution image can get as large as 28 gigabits which frequently will 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 has to be combined. In HiRISE 28 Gbits image case, just because the end of file PDU is received, does not mean the file is completed because the end of file PDU can be coming from the second station at earliest tracking time, and the rest of data is still being transmitted from previous track at another station.
2. 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 for it to appear is very low.

3. The third kind of timer is set such that the file will be produced periodically, for example, once every n hours. This trigger will give the users a warm filling that his/her data is being received and processed as planned.

Re-transmission capability is designed for the MRO to handle data dropout. In order to use the re-transmission capability effectively, the fast frame accountability report, the fast command generation and radiation are essential. Based on the frame accountability report, gaps of the data stream will be identified. The software will generate command sets based on the gaps, the s/c commanding timing, and a set of user specified criteria. Because MRO has weekly nineteen of twenty one 8-hour track, (almost continuous DSN coverage), a schedule command radiation can happen very frequently. As long as the on-board data has not been overwritten yet, data can be downlinked.

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 s/c to ground, those data, in the unit 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. The transaction log file is in one to one relation with the data file. The transaction log files describe the quality of the data and other ancillary information.

4.3 Data Distribution

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

RSDS is supported by multiple dedicated T1 lines connected between JPL and different instrument sites, specifically, University of Arizona, Applied Physics Lab, and Malin Space Science Systems. These dedicated T1 lines are sized to allow for twice the highest daily data volume a site will receive, and has very stringent MTBF

and MTTR. Users can also use internet/internet2 to access RSDS as well.

4.4 Data Accountability

The systems described above is a very capable system, it gives us flexibility to plan, and gives us a great data return. However, the flexibility has its cost. Because of the ephemeris prediction accuracy requirements, we may have planned observations that, when execution time comes, violates the flight rules, such as $> 30^\circ$ in roll angle. We may also have squeezed more observations than we are allowed to; hence, lost some data. The MRO employees an end to end data accountability system to help the users to identify where their data are. Starting from the planning cycle, products prediction system takes the planning results as inputs, update throughout the execution cycle, provides science team with up to date expected product lists for each instrument. Status telemetries are generated as the command files are uploaded to 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 correlate the predicted product and its status as it traverse through the spacecraft data system and ground data system, and provide the correlated information similar to the tracking systems used by many commercial transportation companies to the science users.

5.0 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 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.

MRO successfully accomplished its system-level Critical Design Review (CDR) in May 2003, followed by the successful ATLO (Assembly, Test, and Launch Operations) Readiness Review in March 2004 and the subsequent of ATLO activities. MRO was launch on August 12, 2005 with science data acquisition commencing in November 2006 once the MRO spacecraft has reached its primary science orbit. Science

operations will be conducted for at least one Martian year (~two Earth years). Immediately after the science phase, the MRO spacecraft will begin its relay phase. This phase will continue until the planned end of mission - December 31, 2010. Attitude control propellant was loaded on the vehicle so that if a mission extension is desired, the vehicle could continue to function as a relay spacecraft with the Electra payload until the year 2015.

6.0 SUMMARY

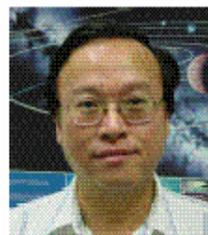
MRO is a major mission of the Mars Exploration Program. This mission will greatly enhance our understanding of Mars by returning new and high resolution scientific observations. The MRO spacecraft and its scientific payload reflect a state of the art design for planetary exploration. Over the course 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.

7.0 REFERENCE

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8.0 BIOGRAPHY

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 Ground Data System and Mission Operations System in many missions including Mars Global Surveyor, Stardust and Mars Odyssey missions. Currently, he is the Mission Operations System Manager of the Mars Reconnaissance Orbiter Project.



9.0 ACKNOWLEDGEMENT

The research described in this (publication or paper) was carried out at the Jet Propulsion Laboratory, California

Institute of Technology, under a contract with the
National Aeronautics and Space Administration.