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MARS RECONNAISSANCE ORBITER MISSION

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Abstract

The Mars Reconnaissance Orbiter (MRO) will be launched in August 2005 by an intermediate-class expendable launch vehicle from Cape Canaveral Air Station USA. It will deliver to Mars orbit a payload to conduct remote sensing science observations, characterize sites for future landers, and provide critical telecom/navigation relay capability for follow-on missions. The mission is designed to provide both global and targeted observations from a low 200 by 400 km Mars orbit of with a 3:00 P.M. local solar mean time (ascending node). During the one Martian year (687 Earth days) primary science phase, the Orbiter will acquire visual and infrared high resolution images of the planet's surface. After this science phase is completed, the Orbiter will provide telecommunications support for spacecraft launched to Mars in the 2007 and 2009 opportunities. The primary mission ends on December 31, 2010, approximately 5.5 years after launch.

Introduction

Understanding Martian evolution and the processes occurring on its surface today are in flux. The Viking mission enabled a major step forward in our knowledge of the planet, but at the same time generated new questions and mysteries that follow-on missions today are still attempting to answer. The overarching goal of NASA's Mars Exploration Program (MEP) is to address some of those mysteries in order to determine whether life ever existed on Mars. The scientific objectives established by the NASA MEP have 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. Finally, water is a resource that can be exploited in the future when humans go to Mars.

By capitalizing on advances in spacecraft technology and launch vehicle capability, NASA MEP is planning more ambitious missions in the upcoming decade to address these critical themes. Landers launched in 2003 and 2007 will provide unprecedented in situ measurements of surface properties, however, these measurements cover relatively small geographic areas on the Martian surface. In order to expand the critical measurement suite and extrapolate these ground truth measurements from landing sites to the entire planet, the MRO mission is planned for launch in the 2005 opportunity. An artist rendering is shown in Figure 1.

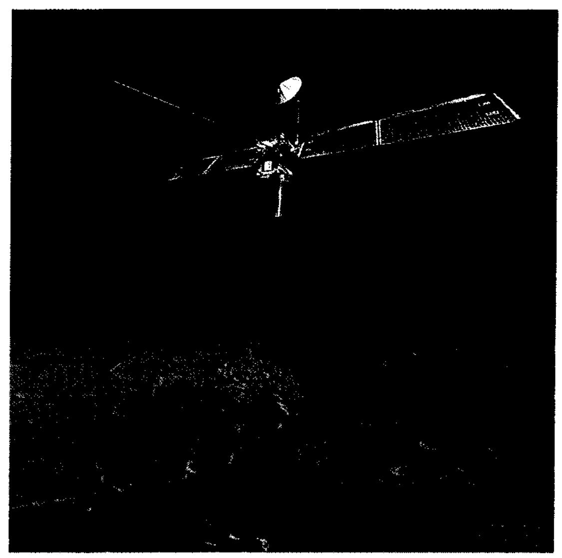

Figure 1. Artist rendering of MRO over chaotic region of Valles Marineris.

Imaging the surface at a resolution 5 times better than any prior mission, MRO will dramatically expand our understanding of Mars. The reference science payload for the mission consists of a high resolution imager (capable of resolving $\leq$30 cm/pixel at 200 km 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, which will provide a proximity link to the surface and approach navigation support, and an optical navigation camera, which will demonstrate precision entry navigation capability for future landers.

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

The downlink data rate from Mars to Earth has always constrained the total science return from Mars missions. Driven by limited onboard power, the physical size of the aperture, and launch vehicle capability, the overall science return from many recent missions has been strangled. The MRO mission takes advantage of advances in launch vehicle capability and in spacecraft technology, such as increased onboard data throughput and solid state data storage, to increase, by an order of magnitude, the returned data volume, and consequently, the coverage and resolution of the surface. Enabling this level of returned data volume challenges not only spacecraft design but also the ability to process and distribute the products on the ground.

Requirements

There are three broad objectives which the science and engineering payloads support: science investigation, site characterization, and telecommunications (relay) support.

MRO Science Investigation

In support of detailed science investigations, the orbiter will conduct remote sensing of the surface for 1 Martian year (approximately 687 Earth days). The science measurements will enable the following theme-related objectives to be achieved:

- Understand the present climate and geology of Mars and the processes which control them:
  - *Characterize the seasonal cycles of water, dust, and carbon dioxide;*
  - *Characterize the Martian atmosphere* in terms of its thermal structure, mass transport, and interaction with the surface;
  - *Map in detail surface stratigraphy and composition*;
  - *Probe the subsurface of Mars* to survey its geologic variability and to search for evidence of present-day near-surface liquid water and ice;
  - *Explore the subsurface structure of the polar caps and adjacent layered terrain.*
- Understand the past climate of Mars and the role of water:
  - *Search for sites showing evidence of aqueous mineralization;*
  - *Observe detailed geomorphology and stratigraphy of key locales* to characterize features indicating the presence of liquid water on the surface of Mars at some point in the planet's history.
- Identify regions and locales of exceptional scientific interest for future exploration:
  - *Remotely explore hundreds of local areas* on Mars at unprecedented spatial and spectral resolution;
  - *Search the surface and subsurface for anomalous regions* of high scientific interest.

MRO will also produce the climate science data sets that were to have been provided by the Mars Climate Orbiter (MCO) payload, which was lost in 1999. When combined with data sets from MGS and Mars Express, MRO will also help characterize diurnal, seasonal, and interannual climate variability by observing at different local times and during a different Mars year than the other two missions.

MRO Site Characterization

- Enhance future mission success by finding the sites of greatest interest and scientific promise:
  - *Find exciting new sites* for exploring the surface or subsurface;
  - *Characterize all key sites* to support the design and implementation of future missions.

Only a small percentage of the Martian surface will have been surveyed at high spatial resolution (resolutions < 10 meters per pixel pair) by the time of the MRO launch. Thus, a primary goal for MRO is to find and characterize the locales on Mars that will become the primary targets for future spacecraft missions to Mars. This examination of the surface will serve two purposes: to identify hazards to landers and to locate scientifically interesting sites for in situ investigations. Figure 2 depicts the resolution differences between the best images of the surface from orbit to date and that planned for MRO.

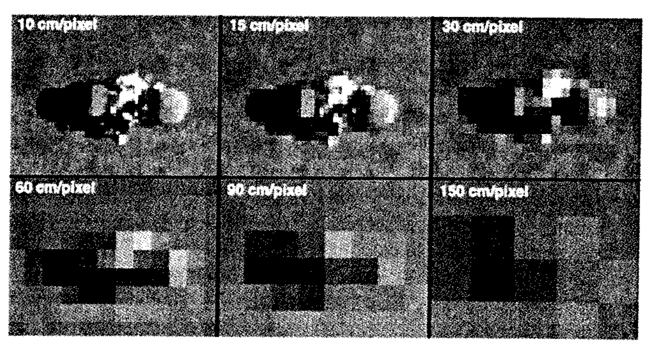

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Figure 2. Differences in resolution of features on Martian surface. 150 cm/pixel is the best any camera has achieved to date. 30 cm/pixel is the required MRO resolution.

MRO Relay Support

- Relay data from other Mars missions while MRO is operating at Mars:
  - *Increase the amount of data that can be returned from landed assets* by using the orbiter power and telecommunications assets;
  - *Reduce the power required for data return from landed assets* by allowing power needed for direct-to-Earth communications to be split between orbital relay and enhanced surface activities (e.g., roving, drilling, observing).
  - *Provide a navigational capability which can enhance the accuracy of Mars atmospheric entry or Mars orbit insertion.*

The third major objective is to provide a relay link from the surface of the planet back to Earth and to support incoming missions with navigation measurements. Future landers will require accurate entry into the Martian atmosphere in order to support the tight landing area requirements. MRO will provide Doppler measurements by receiving the traditional downlink signal from the incoming spacecraft, thereby providing another independent measurement of spacecraft position and velocity. After landing, one of the largest problems is getting high data volume off the surface of Mars and back to Earth. Carrying an UHF transceiver common to other spacecraft such as Mars Express, MRO is part of a new telecommunications infrastructure that will dramatically increase the bandwidth from the surface to Earth.

Payload Description

To achieve the scientific objectives outlined above requires the development of many new science instruments. The instruments are functionally divided into global mappers, regional surveyors, and high resolution, targeting images. The MRO science payload will include the following instruments:

- High-Resolution Imager
- Visible-Near Infrared Imaging Spectrometer
- Atmospheric Sounder
- Wide-Angle Color Imager
- Shallow Sub-surface Sounding Radar
- Context Imager

The Wide-Angle Color Imager and Atmospheric Sounder are derived from MCO experiments designed to achieve the climate objectives outlined earlier. These two instruments are the global mappers. They are strictly nadir pointed, relatively low data rate and continuous operations instruments. Although specific allocations have not been made, together, they are expected to use 10% or less of the available data bandwidth.

New targeting instruments include a High Resolution Imager and a Visible-Near IR Spectrometer which will observe selected areas at resolutions an order of magnitude better than instruments having flown prior to MRO. These instruments require precise along track timing as well as cross tracking pointing of up to 30° from the orbiter to enable imaging of a vast number of high priority targets on the surface.

The High Resolution Imager observes targeted swaths of Mars which are a few kilometers wide and tens of kilometers long at unprecedented spatial resolutions, varying from 30 cm to 60 cm as the spacecraft altitude varies from 200 to 400 km in its near-polar, moderately elliptical orbit. The lowest periapsis will walk around the planet in a 60-day cycle, providing opportunities to view nearly all sites from altitudes less than 250 km. Prior to the arrival of MRO, the highest spatial resolution achieved by previous spacecraft (MGS and Mars Express) will have been ~ 1.5 meters.

The MRO Imaging Spectrometer has a spatial resolution on the order of 50 m from an altitude of 400 km, as compared to a resolution of a few hundred meters for the Mars Express instrument. This scale enables a search for evidence of prior hot springs, thermal vents, or lakes and ponds. If water were present for an extended time in such regions, it should have left deposits of minerals whose spectral signature can be detected at near-infrared wavelengths. The spectrometer's resolution and wavelength range permits observations for these features.

Another camera on MRO will provide context imaging for the high-resolution targeted observations by observing simultaneously with the High Resolution Imager and the Imaging Spectrometer, but at intermediate resolution (~ 10 m) and with greater coverage (> 30 km swath). MRO's radar sounder operates at frequencies near 10 MHz. This radar complements measurements by the radar on Mars Express, which will operate at lower frequencies, and plans to penetrate up to a few kilometers into the ground. The depth of penetration for the MRO radar (< 1km) will be shallower than that of the Mars Express radar, and so MRO will probe the near-surface structure and composition. The detection of anomalous regions, which may reflect ground ice or even subsurface liquid water, will help to focus the targeting of surface observations from MRO and support the design of future landed missions. In addition, the profiling of the Martian permanent polar caps by the MRO and Mars Express radars will yield new, more definitive observations with regard to subsurface structure and the presence or absence of liquid water near the icy surface. The context imager and the radar are the two regional investigation instruments.

Tracking the spacecraft from Earth while it is in a low polar Mars orbit provides the opportunity to map the gravity field in greater detail than before and to characterize fine-scale structure in the atmosphere through radio science techniques. Better knowledge

of the gravity field provides greater insight into the geological structures of the surface and near-surface and into the geophysical processes which produce them. Finally, the recording of atmospheric drag effects during the period in which the spacecraft aerobrakes into its primary science orbit provides a unique characterization of atmospheric densities at high altitudes (~ 100 km). This enables an understanding of high altitude processes, such as the loss of water vapor to space, and for characterizing the environment which future missions will encounter.

One of the more challenging aspects of MRO's operations in its science campaign will be the choice of localized regions for high spatial resolution images. This will be done using data sets from previous missions like MGS, Odyssey and Mars Express and using data from MRO itself. In addition, MRO will target past landing sites, such as Viking, Pathfinder and the Mars Exploration Rovers, both to characterize those sites further and to compare the remotely sensed and in situ data. Landed investigations have the greater measurement sensitivity that near-field and in situ instrumentation can provide, while the orbiter benefits from its regional and global reach. This mutual validation of the landed and orbital remote sensing data is an important part of the MEP. With its unprecedented spatial and spectral resolutions, MRO science instruments can close the resolution gap between orbital and landed measurements, while continuing to characterize hundreds of globally distributed targets throughout its mission.

The engineering payload consists of the telecommunications package which provides the proximity link to the surface and approach navigation support, and an optical navigation camera which demonstrates precision entry navigation capability for future entry vehicles. The telecommunications package provides a near omni-directional coverage to both in situ surface and orbiting assets. It contributes navigational-related data in the form of one way Doppler measurements through the use of its Ultra Stable Oscillator and two way Doppler measurements through the use of a transponder on the corresponding spacecraft or landed asset. It also provides one and two way ranging measurements.

Working at UHF band, the transceiver supports forward and return simplex and full-duplex links. It is a store and forward system enabling communications with assets not in view of the Earth. The mass allocations for the different payload elements are in shown in Figure 3.

Instrument	Mass (kg)
Atmospheric Sounder	9
Wide Angle Camera	4
Radar	16
Spectrometer	30
Hi Res Imager	52
Total Science	111
Communication Gear	20
Optical NAV Camera	4
Total Payload	135

Figure 3. Total payload mass allocation including reserves.

Mission Design

The 2005 Mars launch opportunity is the most demanding one of the decade from the point of view of required injection energy. With a required injection energy (C3) of 18.1 km^2/s^2 to a declination of the launch asymptote of 40° for a throw mass of 1800 kg, the mission requires one of the new class of intermediate-class expendable launch vehicles: Atlas 3 or 5, or Delta III or IV. The launch period is a three week period beginning August 8 and ending August 28, 2005. The seven month, type 1 trajectory results in an arrival period with a duration of nine days from March 3-11, 2006. The mission overview of events is shown in Figure 4 A and B.

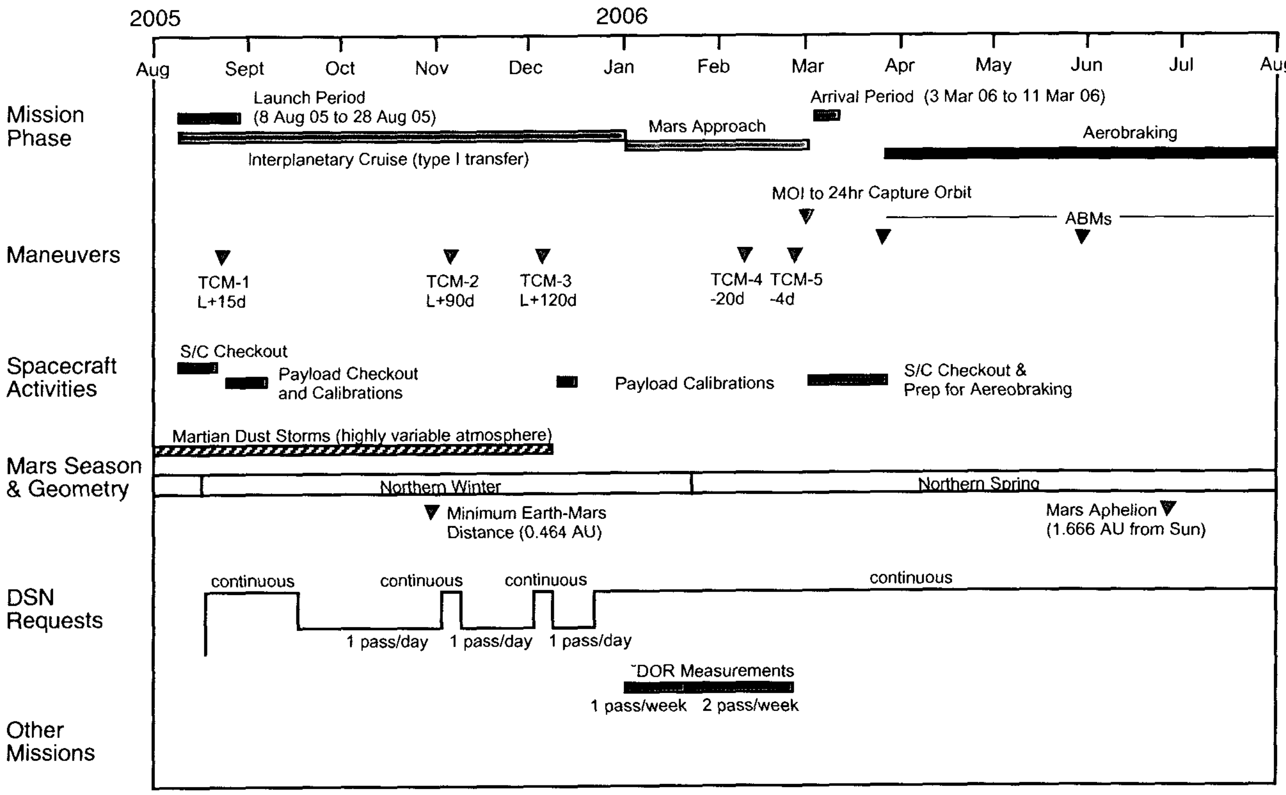

Figure 4a. MRO mission overview - The period covered is from launch through start of aerobraking.

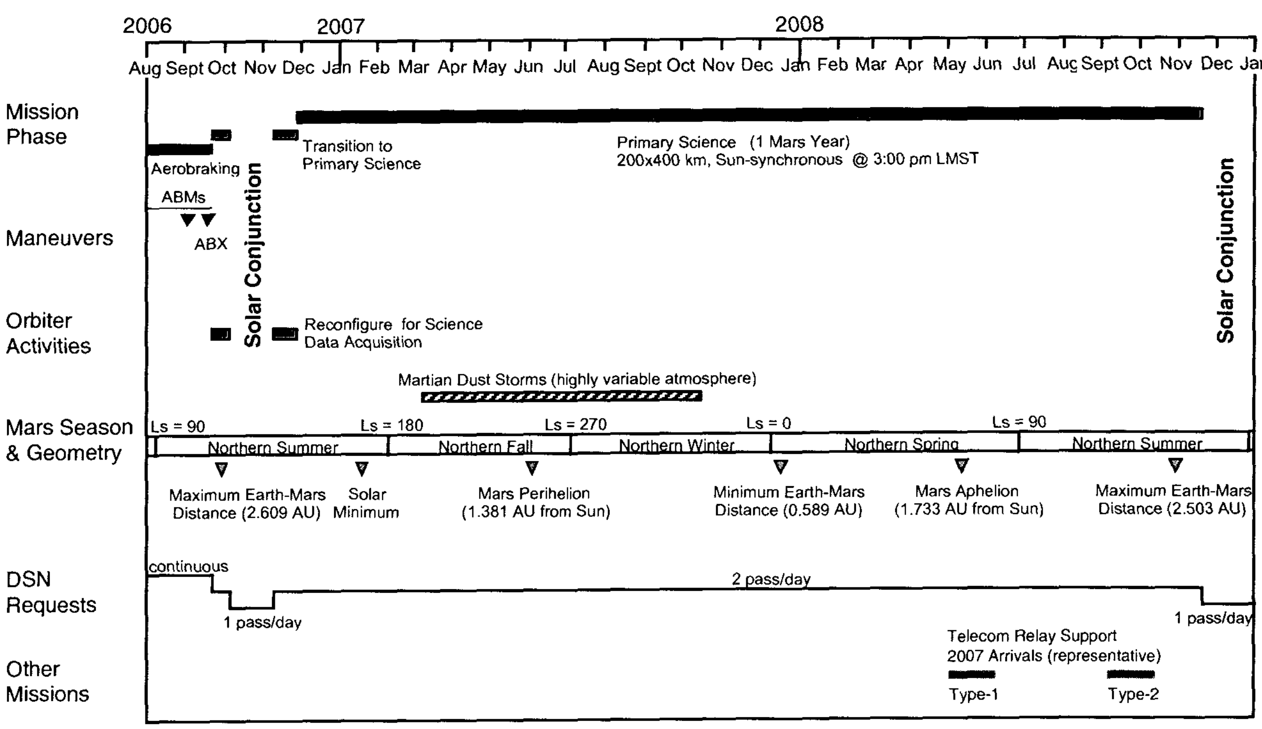

Figure 4b. MRO Mission overview covering from aerobraking through the end of the primary science phase. (Relay phase not shown)

The interplanetary cruise trajectory is ballistic and requires no large deep space maneuvers. Several (five at present) small trajectory change maneuvers are planned for this phase. During cruise, orbiter and instrument check out and calibration are performed.

On approach to Mars, the OpNav camera images the moons of Mars against the star background. This data is not critical to the success of the MRO Mars orbit insertion but it does provide data for confirmation of algorithms and software code for the camera's use in future missions. No additional instruments will be operated on Mars approach.

MRO approaches the planet toward the south pole with 3 km/s of excess hyperbolic velocity. Mars Orbit Insertion (MOI) requires 1100 m/s delta V to insert into a 35 hour highly elliptical orbit with a periapsis altitude of 300 km and an ascending node at 9:00 P.M. local mean solar time (LMST). Six months have been allocated to perform aerobraking to reach the final primary science sun-synchronous orbit of 200 x 400 km. The final science orbit is near polar with an inclination of 92.8°. During the aerobraking phase, the orbit equator crossing time moves from the 9:00 P.M. arrival node to the science node of 3:00 P.M. +/- 15 min (both ascending). The main advantage of the 200 x 400 km elliptical orbit over the 400 km near-circular orbit used on previous missions is the potential increase in ground spatial resolution by up to a factor of 2. High-resolution observing can still be targeted globally since the gravity field of Mars will move the periapsis latitude around the planet, as shown in Figure 5. In the baseline orbit, the periapsis rotates once around the planet every 60 days. The equator crossing time is a compromise between the desires of the visible imaging objectives, which favor later crossing times (e.g. 4:00 P.M.) for the surface contrast provided by low sun angles, and those of the spectrometer objectives, which favor a midday crossing to increase the amount of reflected light, i.e. better signal-to-noise.

The primary science phase will last approximately one Martian year (687 Earth days). This duration enables investigation of all the seasons. During this phase, there will be 16 hours per day of coverage provided by the Deep Space Network 34 m stations via X band. The Martian year of coverage enables all seasons to be covered, thereby satisfying one of the key science objectives. The completion of the primary science phase ends formal operation of the instruments and the science investigators have eight months to complete processing of all their data and provide the complete data set to the Planetary Data System for archiving. Science investigation may continue after this point but only as an extended mission. Orbiter design allows for simultaneous operation of the relay equipment and the science instruments. Upon completion of the science phase, the relay phase will commence and will also last approximately one Martian year. During this phase, there will be 8 hours per day of DSN coverage and the orbiter will support landers and incoming spacecraft At the end of its useful life, the orbiter will be transferred to a circular 430 km orbit to satisfy planetary quarantine requirements. The prime mission will end on December 31, 2010, roughly 5.5 years after launch. However, the spacecraft will be loaded with enough propellant to last for ten years of operation.

Both after aerobraking is completed and near the end of the primary science orbit, superior conjunction will interrupt communications between the Orbiter and Earth. Conservatively, communications will be lost for approximately one month. During that period the spacecraft will be safed, although a study will be performed later this year to see if the Orbiter can maintain limited data acquisition for the global mapping instruments.

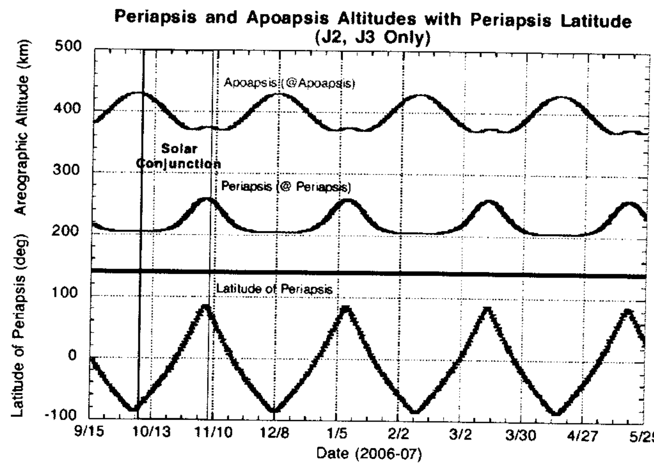

Figure 5. Variation in both latitude of periapsis as well as altitudes over a typical nine-month span

Mission Operations

Mission planning, navigation, sequence and command generation, and real time operations is conducted by a combined team from JPL, the Orbiter contractor, and the instrument providers. The MRO ground system will receive and distribute the raw data from the stations out to the appropriate organizations. The orbiter contractor provides engineering support including trend analysis, anomaly investigation and recovery, orbiter health and welfare monitoring, performance calibration, and engineering sequence and command request generation. The PIs provide science command request and perform data processing and analysis from their home institution.

The mission will use X band and has baselined the use of 34 m BWG stations. The 70 m stations will be used to enhance science return whenever it can be reserved. The comparison between the 34 m and the 70 m stations are shown in Figure 6.

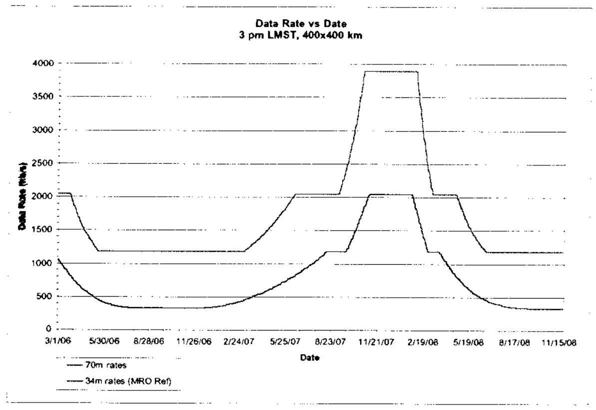

Figure 6. Comparison of data return rate to both a 34 m (lower line) and a 70 m (upper line) antenna as function of Mars-to-Earth distance.

Tracking capability includes 1 & 2 way coherent Doppler, ranging, commanding and telemetry transfer. During the cruise phase, coverage is planned for one 8-hour pass per day except around the TCMs, where coverage will be continuous. For Mars orbit insertion and the aerobraking phase, coverage is continuous. The primary science phase requires two 8-hour passes while in the relay phase there is only one pass planned.

One of the unique aspects of the MRO mission is the volume of data generated in comparison to other planetary missions. The average daily volume varies from 16 to 126 Gb/day depending on the Earth-to-Mars range. At the maximum range of 2.67 AU, the minimum data rate to a 34 m DSN antenna is 280 kb/s. At these rates and volumes, MRO will return over 10 times the data volume of Cassini and almost 25 times that of Odyssey, as shown in Figure 7.

This data volume creates a challenge not only in flight but on the ground. A study is planned for later this year to determine the most economical way for data to be processed and distributed, given the recent advances in data transfer. The present baseline, a decentralized approach, distributes the raw instrument data to the PI's processing facility, has that facility conduct the processing, and then redistribute the data to co-investigators. All major products are sent to the Planetary Data Centers for archiving. In the second concept, a centralized facility is used to process all the data. This facility uses software developed and controlled by the PIs but hosted on machines at this central site. After processing, the higher level data are transmitted to the PIs for analysis. In both cases, the Project copies the raw data as it comes from the stations and archives it. The cost of transmission, and of processing and maintaining the platforms are key factors in the trade study. The capability of the Planetary Data Archive System to handle these data volumes is presently under examination.

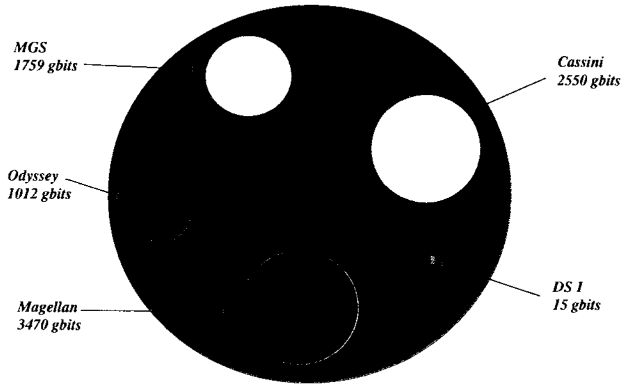

Figure 7. Comparison of total data returned during prime science phases of various planetary missions.

Orbiter Description

As of this writing, the orbiter contractor is not selected and a detailed description of the orbiter can not be defined. However, a minimum set of capabilities is known. The maximum launch mass of the orbiter is 1800 kg of which 135 kg (including payload reserves) is allocated for the science and engineering payloads. Similarly, 200 W of orbital average power is reserved for the payload while in the primary science phase. The orbiter will be compatible with all intermediate-class launch vehicle and provide translational delta V greater than 1383 m/s. The orbiter will be able to function without ground command for up to 30 days during solar conjunction.

The orbiter provides a minimum of 48 Gb of volatile mass memory and a processing capability of 20MIPS for use by the payload. The telecommunications subsystem will support a downlink rate of 280 kb/s at maximum range and 2.2 Mb/s (to a 34 m antenna) at minimum Mars-to-Earth range using an X-band carrier. The maximum downlink bit error rate is 10E-6.

The orbiter provides a high speed low voltage differential signaling serial data interface capable of supporting a data clock rate of up to 30 Mb/s for the high rate instruments and a low speed RS-422 interface operating at 9600 b/s for the low speed instruments. It supports simultaneous real time data transfers for all the instruments. Commanding is via a synchronous serial RS-422 interface.

The Orbiter is capable of pointing <0.7 mrad (3 sigma, roll) and <1.0 mrad (3 sigma, pitch and yaw) and has various stability requirements defined by the payload requirements. The instruments will be mounted on a nadir facing deck and the bus will have the ability to point up to 30° in the cross track direction at least twice per orbit.

Implementation

The MRO mission is managed by the Jet Propulsion Laboratory, and its implementation relies heavily on the capabilities of industry and academia. The Orbiter contractor develops the bus, performs payload accommodations, and provides launch and operations support. The launch vehicle is procured by the Kennedy Space Center via the newly defined NASA Launch Services contract. The major elements of the payload are competed via an Announcement of Opportunity issued by NASA Headquarters.

Schedule

Starting in December 2000, the Project is in Formulation Phase for a total of 19 months. This phase is divided into Phase A which lasts until January 2002 when the Preliminary Mission and System Review is held and Phase B which extends 6 months until completion of the Preliminary Design Review in July 2002. The Implementation Phase extends for approximately 3 years until the August 2005 launch plus 30 days. The cruise phase lasts for 7 months, Mars Orbit Insertion and aerobraking another 6 months, the primary science mapping phase for 2 Earth years and the relay phase for another 2 Earth years.

Summary

MRO represents the first in the new generation of Mars missions utilizing the capability provided by the new class of intermediate class launch vehicles. It enables resolution of the Martian surface at an order of magnitude beyond any other mission. Its global viewing and targeted instruments provide critical data to support both a myriad of scientific investigations and site characterization for future landers. The engineering payload provides support to future missions by testing the experimental optical navigation camera and by operating telecommunications relay equipment.

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