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Challenges of In-Flight Calibrations for the Mars Reconnaissance Orbiter Payload

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The Mars Reconnaissance Orbiter is the most complex spacecraft that has ever been sent to investigate the Red Planet. A major part of what makes this mission so complex is the suite of instruments that were selected. The instruments on MRO vary from a simple imaging system, not much larger than a pocket knife to the largest camera ever flown to another planet. Not only does the size of the instruments vary, so do the scientific investigations associated with each instrument. In order to ensure that this payload suite would be able to satisfy all of its science objectives, a major effort was put forth by the MRO Project to ensure these instruments were well calibrated prior to the start of the Primary Science Phase. The in-flight calibration plan for MRO proved to be quite challenging, given the often conflicting requirements due to the varying capability of each of the instruments and the desire to constrain the workload on the Mission Operations personnel. The quality of data returned by MRO since the start of the Primary Science Phase is a tribute to the effort that was put forth to characterize the in-flight performance of the instruments. This paper will describe the challenges associated with the planning and implementation of the various calibration events on MRO, and will exhibit some of the results from those calibrations.

I. Introduction

THE Mars Reconnaissance Orbiter (MRO) is the newest component of the Mars Exploration Program to be returning data from orbit. This mission combines a suite of highly capable scientific instruments with an unprecedented low-altitude orbit to produce the highest resolution data set available to date. In preparation for the intense scientific campaign to thoroughly examine the atmosphere, surface, and subsurface of Mars, the MRO Project put forth an aggressive effort to calibrate the in-flight performance of its scientific payload prior to the start of the Primary Science Phase (PSP) of the mission.

Throughout the effort to define the in-flight calibration plan, there were numerous challenges which had to be overcome. These included separating requirements from “desirements”, satisfying schedule and resource constraints, and finally, implementing the plan. To resolve these issues, the MRO Project established the Calibration Working Group (CAWG). The CAWG consisted of members from all elements of the Project, namely Mission Design and Navigation, Flight System, Science, and Mission Operations to ensure continuity from development through implementation and execution. One of the group’s first tasks was to establish high level guidelines and constraints that needed to be followed. For instance, these guidelines indicated how closely together activities could be scheduled, and specified that interaction with the spacecraft should be minimized. Concurrently with these guidelines, other Project Requirements had to be satisfied. These requirements defined blackout periods during the mission when calibrations could not be performed. These included the periods before TCM-1 (planned for Launch + 15 days), within ± 3 days of any maneuver, and within 30 days of Mars Orbit Insertion (MOI). The next challenge addressed by the CAWG was planning and scheduling calibrations to avoid overwhelming the Flight Operations team, which also had to focus on preparing for the MOI maneuver. This planning process determined how long an activity could last and when it would occur. Lastly, the group had to define the details needed to implement the activities. This area was particularly challenging given the often conflicting needs of the instrument teams.

In addition to calibrations needed for the payloads, checkouts and calibrations of the engineering subsystems were also necessary to ensure that the entire system would work as expected once MRO reached orbit. This paper

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focuses on the MRO payload calibrations, which proved to be a more complex systems problem to solve than the engineering calibrations.

After all of the Cruise Phase and Transition Phase calibrations had been performed, the MRO spacecraft was well prepared to execute its planned science investigations.

II. Payload Description

There are six science instruments on the MRO spacecraft varying from a simple imaging system no larger than a pocket knife to the largest camera ever flown to another planet. Not only does the size of the instruments vary, so do the scientific investigations associated with each instrument. Table 1 describes the scientific objectives of the instrument teams, and Table 2 describes the capabilities of these instruments.

A. CRISM (Compact Reconnaissance Imaging Spectrometer for Mars)

The Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) is a hyperspectral imaging spectrometer provided by the Johns Hopkins University Applied Physics Laboratory. It is used to identify key mineralogical indicators of water and hydrothermal systems at spatial scales smaller than a football field. The Optical Sensor Unit, which consists of a visible/near infrared (VNIR) spectrometer and an infrared (IR) spectrometer, is mounted on a gimbal which allows it to follow a specific target on the surface as the orbiter flies overhead. The gimbal has a range of ±60 degrees in the along-track direction, which allows for long integration times and high signal-to-noise ratio data to be obtained. The IR detector is cooler by three cryo-coolers, which operate one at a time.

The key calibration objectives for CRISM were to obtain radiometric, geometric, and alignment data.

B. CTX (Context Camera)

The Context Camera (CTX) is a Facility Instrument built and operated by Malin Space Science Systems and the MRO MARCI science team. It consists of a 350mm focal length, 6-degree field of view, catadioptric Cassegrain (Maksutov-type) telescope that images onto a 5064 pixels-wide charge coupled device (CDD) line array. The CCD detects a broad band of visible light from 500 to 800 nanometers in wavelength. This instrument is used to provide context for images acquired by the other instruments onboard the Mars Reconnaissance Orbiter.

The key calibration objectives for CTX were to obtain geometric and alignment data.

C. Electra

The Electra payload is an advanced ultra-high-frequency (UHF) telecommunications package that is an engineering instrument which will provide high-rate communications and precision navigation support to in-situ assets at Mars. The Electra payload allows the spacecraft to relay commands from the Earth to surface assets and to return high volumes of science and engineering data from those assets back to Earth using MRO’s more powerful direct-to-Earth telecommunications system. Electra was developed and operated by the Jet Propulsion Laboratory/ California Institute of Technology.

The key calibration objectives for Electra were to obtain information on the antenna pattern and UHF performance.

D. HiRISE (High Resolution Imaging Science Experiment)

The High Resolution Imaging Science Experiment (HiRISE) is a visible and near-infrared camera capable of providing images of the Martian Surface in unprecedented detail. Provided by the University of Arizona, HiRISE has an aperture of 50 cm and a 1.15-degree field of view. There are 14 detectors, staggered across the focal plane, to provide full swath coverage without gaps. 10 detectors provide data in the red wavelength band, 2 detectors each provide data in the blue-green and infrared bands.

The key calibration objectives for HiRISE were to obtain radiometric, photometric, and alignment data.

E. MARCI (Mars Color Imager)

The Mars Color Imager (MARCI) is a wide angle camera provided by Malin Space Science Systems which is designed to acquire daily global images of Mars for at least 1 Martian year at 5 visible wavelengths and 2 ultraviolet wavelengths.

The key calibration objectives for MARCI were to obtain radiometric and alignment data.

F. MCS (Mars Climate Sounder)

The Mars Climate Sounder (MCS) is an instrument which measures changes in atmospheric temperature or composition with height. The measurements provide data on the temperature, humidity, and dust content of the Martian atmosphere.

The key calibration objectives for MCS were to obtain photometric data.

G. ONC (Optical Navigation Camera)

The Optical Navigation Camera (ONC) on MRO was primarily a technology demonstration of a supplemental navigation aid for future missions. The ONC is a 1x1 degree square field-of-view that can image the moons of Mars to better assess the spacecraft location relative to Mars. The ONC was developed and operated by the Jet Propulsion Laboratory/ California Institute of Technology.

The key calibration objectives for ONC were to obtain geometric and photometric data.

H. SHARAD (Shallow Radar)

The SHARAD instrument is a shallow subsurface radar capable of penetrating a few hundred feet (up to 1 kilometer) below the surface. The instrument consists of a10 meter antenna mounted on the back of the spacecraft that transmit in the 15-25 MHz frequency band. The instrument is provided by the Italian Space Agency

The key calibration objectives for SHARAD were to obtain measurements on the electromagnetic interference (EMI) levels of the spacecraft.

Team	***Type***	***PI/TL, Institution***	***Attributes***
ACCEL	**Upper Atmosphere Structure Investigation**	***Gerald Keating, TL*** **George Washington U.**	**Profile upper atmosphere using S/C Accelerometers during Aerobraking**
CRISM	**Compact Reconnaissance Imaging Spectrometer for Mars**	***Scott Murchie, PI*** **Applied Physics Laboratory Johns Hopkins University**	**Hyperspectral Imaging Moderate spectral/spatial Targeted Obs. Multi-spectral Regional Survey Emission Phase Function Sequences Very High Data Rate**
CTX	**Context Imager**	***Michael Malin, TL*** **Malin Space Science Systems**	**High Resolution Imaging High Data Rate**
MARCI	**Mars Color Imager**	***Michael Malin, PI*** **Malin Space Science Systems**	**Daily, Global Mapping Moderate Data Rate**
MCS	**Mars Climate Sounder**	***Daniel J. McCleese, PI*** **Jet Propulsion Lab / Caltech**	**Daily, Global Limb & On-Planet Mapping; Low-Data Rate**
SHARAD	**Shallow Subsurface RADAR**	***Roberto Seu, TL / PI*** **University of Rome** ***Roger Phillips, DTL***	**Regional Radar Subsurface Profiling High Data Rate**

Table 1: MRO Selected Instruments

Instrument	**Capabilities** (ref. to 300 km)	**Instrument**	**Capabilities** (ref. to 300 km)

CRISM	*High-res. Target* 18 m/pixel 10.8 km swath 6.5 nm 0.4 - 3.96 μm *Multi-spectral survey* 60 chs; ~200 km/bin	**MARCI**	180˚ FOV 7 bands from 0.28-0.8 μm 5 VIS: 1-7 km/pixel 2 UV: 10 – 30 km/pixel Daily Global Mapping
CTX	6 m/pixel 30 km swath Panchromatic (minus blue) SNR > 20Stereo by Revisit	**MCS**	Broadband Solar Channel & 8 Thermal IR Channels 0 - 80 km; 5 km vert. res. Globally Distributed, Daily Atmospheric Limb & On-Planet Observation
HiRISE	0.3 m/pixel Red (6 km swath) Blue-Green & NIR (1.2 km swath) SNR ≥ 150 Stereo by Revisit	**SHARAD**	20 MHz (fo, central frequency) 6 km x 1 km (SAR processing down-track) Profile to ~0.5 km with vertical resolution ~ 10 m (15 m in free space)

Table 2: MRO Instrument Capabilities

III. Requirements versus 'Desirements'

The initial challenge for the Calibration Working Group was to define the scope of the calibration plan. In order to do this, each of the science teams was asked to provide a list of activities that were necessary to calibrate their instruments. The initial compiled list of activities was comprised of 21 different activities. The science teams also provided other specifics for each of these activities, such as the spectral type of the desired stellar target, the size of the image in pixels, or the number of observations needed.

As a starting point for determining the feasibility of any of the activities on the list, the cruise geometry had to be known. Using the most recent spacecraft trajectory information, numerous data sets were produced which provided insight into the spacecraft position as a function of time.

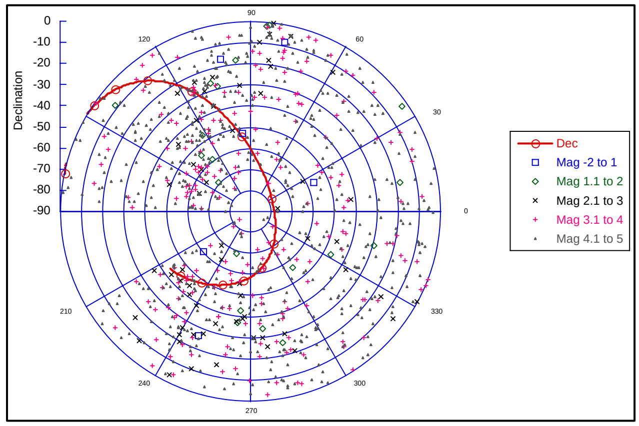

Figure 1: Nadir Deck Pointing During Cruise

Figure 1 shows the nominal pointing direction, in Right Ascension and Declination, of the instrument deck during the Cruise Phase. This data was used to help select stellar targets which would not require the spacecraft to deviate too far from its nominal attitude.

After the group had an improved view of the targets that were desired, the CAWG proceeded to further evaluate the proposed activities to determine their feasibility. The group studied the spacecraft-related geometry for each of the proposed calibrations, such as the slew angle required to reach a specific target, and whether or not the maneuver was safe for the instruments relative to the sun. Figure 2 shows the angle between the Z axis of the spacecraft, where the instruments are located, and the Sun while observing the target M44.

Another focus of the group at this time was to find ways of combining some of the 21 desired observations. Since nearly every instrument team listed the Earth, its moon, or Mars as a calibration target, it seemed natural to try and combine these into the same activity. A similar effort was expended for stellar targets as this was another popular source of calibration targets. By combining observations in this manner, the CAWG managed to condense the number of instrument calibration activities into only eight science activities.

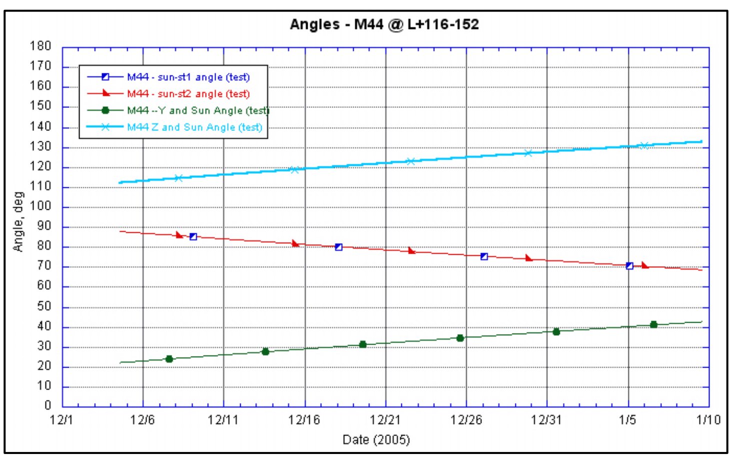

Figure 2: Feasibility Analysis for Proposed Stellar Calibration Target

The most challenging aspect of this portion of the task was the lack of resources from the science teams to examine and respond to requests from the CAWG. Although the CAWG was able to perform analyses independently, a review was conducted at high-level project meetings as means of validating the analyses performed. During this period in the MRO Development, various engineering teams (in particular, the instrument designers) were busy finalizing their designs, which meant that there were very few resources, if any at all, dedicated to Operations planning. Without input from those who were actually designing the instrument, it was difficult to determine which activities were better performed on the ground pre-launch, and which were better performed in-flight post-launch.

One example of this was the MARCI UV Calibration. As part of the feasibility study, the expectation was that a UV-bright star would be used as the source for this calibration. However, as information about the actual performance of the MARCI detectors became available, there was uncertainty about whether or not MARCI would be capable of "seeing" stars. This forced a change to the original list of activities, ultimately resulting in the need to obtain permission from the Project to violate one of the calibration keep-out zones.

IV. Schedule and Workload

With the list of required calibrations reduced to the absolute minimal set, the next challenge for the CAWG was to find the right time to perform each calibration. The calibrations were being planned for the Cruise and Transition Phases of the mission. The Cruise Phase stretched from shortly after Launch until shortly before the spacecraft's arrival at Mars. The Transition Phase spanned the period from the end of the Aerobraking Phase until the start of routine science operations in the Primary Science Phase.

The MRO journey to Mars was only 212 days in duration. However, given the Project requirements on when calibrations could take place, the available time to perform them was reduced to 167 days. Furthermore, the cruise timeline included the Thanksgiving, Christmas, and New Year holidays, which further reduced the available time to schedule calibrations. A decision was made to avoid these holiday periods to allow the Flight team, which had been working at a sprint-like pace since before launch, to rest and prepare for the approach to Mars.

One factor that helped determine the dates for the calibrations was the desire to space out activities so that the flight team could rest between activities. Given that the sizes of the MRO Flight Operations team and the Mars Odyssey Flight team were comparable, yet MRO had to operate six instruments compared to Odyssey's three, this was a desperately needed constraint. This led to the seven day rule: calibrations could not be scheduled any closer than seven days apart. The nature of these activities was so complicated that nearly every subsystem of the spacecraft had to be involved in the creation and review of the command products for each science calibration activity. Seven days gave the team enough time to review the results from the previous activity and prepare for the upcoming activity.

Another factor that reduced the workload on the Flight team was to plan activities in a manner did not exceed standard spacecraft capabilities. These capabilities include guaranteed pointing accuracy within 0.11 degrees (2 mrad) and slew rates less than 0.05 degrees per second

With the above operational considerations and capabilities accounted for, it was possible to schedule the activities. For some of the activities, the schedule was already predetermined based on the initial feasibility studies. As part of the studies, certain geometry had been requested by the Science teams, which could only be achieved on specific days of the mission.

One example of geometry driving activity scheduling arose with the planning of the Lunar Calibration. The science teams requested a view that maximized the portion of the moon that is visible from Earth. In order to achieve this, the MRO-Moon-Earth angle had to be at a minimum. The rationale for this illumination requirement was to facilitate comparison of images collected in flight with ground-based observations. The image of the Moon acquired by HiRISE during the Lunar Calibration is shown in Figure 3.

Figure 3.: HiRISE Image acquired during Lunar Calibration on September 8, 2005

The end result of the schedule negotiations was a jam-packed Cruise Phase schedule. Figure 4 shows the MRO Cruise timeline with approximate dates for both engineering and science calibrations. This schedule was so aggressive that there was very little room for repeating or delaying any calibrations without significantly impacting future activities. The light blue diamonds in the timeline identify potential backup dates for a few science calibrations, but the choice of whether or not to use the backup dates (and accept the impact of repeating or delaying

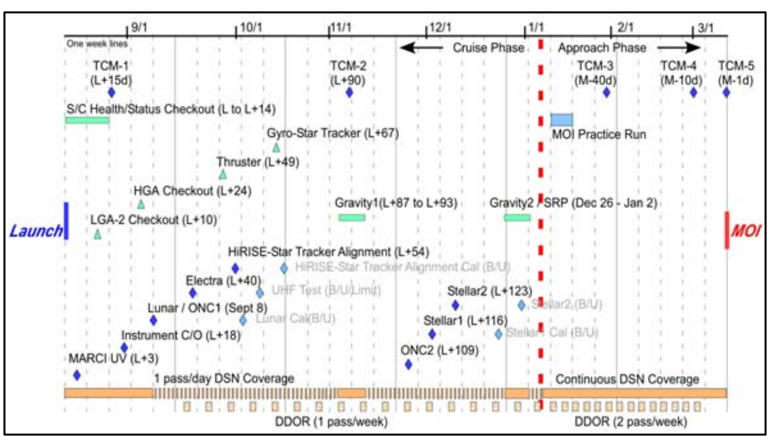

Figure 4: Cruise Timeline

an activity) was left as an Operational decision. The lack of schedule margin mandated especially close coordination with each of the science teams during activity development to ensure a successful outcome.

The other major scheduling challenge was planning for the Transition Phase calibrations. The Transition Phase was the period of time at the end of the Aerobraking phase and prior to the start of the Primary Science Phase where the final instrument deployments and calibrations would take place. However, during the Transition Phase, there would also be a period of unreliable communications while the Sun lay in the path between Earth and Mars during Solar Conjunction. During Solar Conjunction, spacecraft commanding would be restricted and receipt of spacecraft telemetry would not be guaranteed, so activities could not be scheduled during this period.

The goal for the Transition Phase was to devise a plan to maximize the readiness of the Project to commence with the Primary Science Phase once the spacecraft emerged from behind the Sun. Again, a balance had to be found between the goals of the instrument teams and the time available to perform the observations.

The biggest factor that complicated scheduling of activities during the Transition Phase was the uncertainty in exactly when the final desired Aerobraking conditions would be achieved, and consequently, uncertainty in the end date of the Aerobraking Phase. Aerobraking is a technique whereby the spacecraft is expertly dipped through the atmosphere to reduce the orbital energy (and therefore the orbit period) without expending large amounts of fuel. Due to the variability of the Martian atmosphere, the amount of drag encountered during each of these passes could not be predicted in advance. Given this uncertainty, there were three possible aerobraking termination conditions that needed to be accounted for: early, standard, and late[2].

When the actual aerobraking exit maneuver occurred would determine how much time was available for activities prior to the beginning of solar conjunction. Figure 5 shows the strategy for how activities would be prioritized The solid black line represents Solar Conjunction. Activities lying above the black line would take place prior to Solar Conjunction, and those lying below the line would take place afterward.

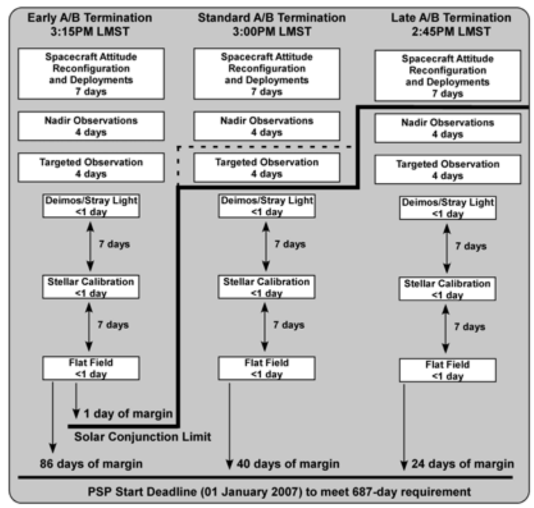

Figure 5: Strategy for Shifting Activities in Transition Phase

V. Implementation

Once the approximate date and time of each calibration was identified, the focus of the CAWG became to specify the detailed information needed to implement the calibration. This is when some of the most challenging issues presented themselves. Because of the tight schedule constraints and the lack of opportunities to repeat failed in-flight calibrations, implementation issues had to be resolved during the development phase, well before launch, necessitating the involvement of the Mission Operations team. A significant contributor to the successful completion of MRO's aggressive in-flight calibration plan was the early involvement of implementers in the development of each calibration.

A. Cruise Phase Calibration

During the Cruise to Mars, there were basically four sources for targets: the Earth, the Moon, Mars, and deep space objects. Considering that each instrument on MRO was designed for a different purpose, their capabilities (and therefore, calibration requirements) varied tremendously. For example, with HiRISE, targets could be smaller, narrower, or fainter, and still be visible, whereas for CTX, targets had to be brighter and wider. For CTX, the rationale was to find a target that would span the instrument's field of view. However, for HiRISE, the goal was to characterize the signal that was reaching the detector.

With the plan already established that multiple instruments could perform observations using the same target, the task now shifted to identifying the target. Without this simplification, the scope of the calibration plan would expand, further increasing the workload on the flight team.

[2] The early, late, and standard designation refers to the Local Mean Solar Time of the orbit relative to the Project Baseline of 3 PM Local Mean Solar Time.

The challenge lay in identifying candidate targets (or sets of targets near each other) which would simultaneously satisfy the needs of multiple instruments. Careful planning and selection of targets allowed the incompressible list of calibrations to be reduced to a smaller, manageable set of flight activities. This was accomplished by combining multiple calibrations into a single activity, albeit a longer and more complicated one. Ultimately, the reduction of the number of flight activities is what allowed the MRO Project to complete all of the calibrations within the tight schedule.

The Cruise Phase calibrations were clearly the most difficult to implement, primarily because of the inexperience of the Flight team with the spacecraft and instruments. Two activities were particularly challenging to implement: the MARCI UV Calibration and the Stellar Calibration.

The first post-launch calibration was the MARCI UV Calibration. Because MARCI had such a low-resolution that it could not use a stellar target, the Earth and Moon system were chosen as imaging targets.

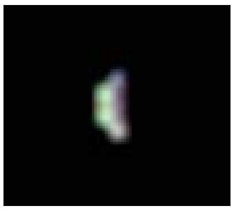

Figure 6: MARCI Image acquired during Earth Calibration

The difficulty did not lie in performing the calibration itself, but arose with the timing of the activity. In order for MARCI to be able to detect the Earth-Moon system, the calibration had to occur within three days after launch. In order to achieve this, more than just the instrument needed to be configured. This activity required earlier than expected configuration of the Command and Data Handing Subsystem for science data, as well as changes to the Power and Thermal states of the spacecraft. The Solid State Recorders (SSR) needed to be powered on to store the data, and the payload decontamination activity had to be delayed. Once all of these impacts were accounted for, the calibration was relatively easy to perform. MARCI has such a large field of view that the Earth and Moon naturally fall within its field of view, requiring only a small slew to scan the detectors across the targets. Figure 6 shows the image that was acquired.

The most challenging calibration of the Cruise Phase was the Stellar Calibration. The original pre-launch plan had the activity occurring over two days, separated by seven days, using two different targets. As the Science teams became more familiar with their instruments, it seemed acceptable to merge the two days worth of observations into one slightly longer day of observations. However, in order to do so, new targets had to be selected. The objective was to find targets in the same region of the sky that satisfied the individual needs of the instruments involved. The targets needed to be close together to avoid increasing the duration of the activity beyond a reasonable amount of time. After an extensive search through stellar catalogs, a solution was found. The CTX target would be the constellation Crux (Figure 7), and the HiRISE target would be the Jewel Box cluster (Figure 8). The targets were close enough together so that not much time was wasted slewing the spacecraft from one part of the sky to another. This saved time, and allowed all objectives to be met in a single day.

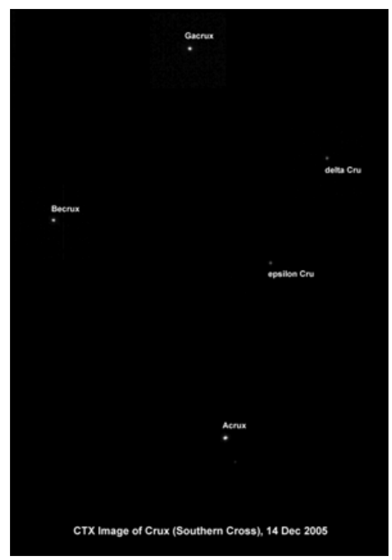

Figure 7: CTX Image of Crux acquired during Stellar Calibration

Figure 8: HiRISE Image of Jewel Box acquired during Stellar Calibration

B. Post-MOI Observations

The next activity that posed a challenge to implement was the post-MOI observations. There were three different components to this activity. First, calibration images would be taken by the HiRISE, CTX, and MARCI. Second, there was an MCS Aerobraking Support Demonstration. Third, there was a jitter test to determine the stability of the spacecraft with all payloads operating in a Science Phase-like configuration.

Part of the challenge in implementing the first part of this activity was controlling expectations. Everyone expected these to be the first high-resolution images of Mars taken by the Mars Reconnaissance Orbiter, but the Project treated these as calibration images, because there were many unknowns associated with taking these pictures. Several first time events were experienced during this activity: the Integrated Target List (ITL) was used to schedule and perform the observations, and the MRO spacecraft attitude was changed to nadir-point.

The ITL is a piece of MRO flight software that autonomously performs the on-board imaging of preselected targets based on the onboard spacecraft ephemeris. Using the ITL made the commanding of these calibration images very different from the calibrations performed during Cruise. During Cruise, the built sequences commanded nearly every aspect of the activity, from controlling the attitude and motion of the spacecraft, to loading and performing the science observations. However, in the case of nadir-pointed observations of Mars, a sequence with different kinds of commanding was required. The new sequence now only needed to control items such as starting and stopping the ITL processing of targets. All other commanding related to the loading of the science observation and taking the science observation was performed autonomously by the spacecraft. Along with the sequence to control the ITL, there were also Mars Ephemeris files which had never been used before.

Figure 9: HiRISE Image acquired during Post-MOI Calibration

For the MCS Aerobraking Support Demonstration, new tables had to be loaded to the instrument so that the right observations were performed. Due to its low resolution, MCS was not able to detect any of the targets imaged during Cruise, so this was the first time the instrument would actually detect a signal in flight. These images show the full disk of Mars taken near the 45,000 kilometer apoapsis of the capture orbit and are different from the normal science mode of MCS involving imaging small cross sections of the atmosphere. From 300 kilometers

One other MCS observation that turned out to be quite unique was the thermal scan of the MRO instruments on the nadir deck, shown in Fig. 11. From left to right, the prominent objects in the images are CRISM, thrusters, MARCI, Electra in front of the solar panels, and HiRISE.

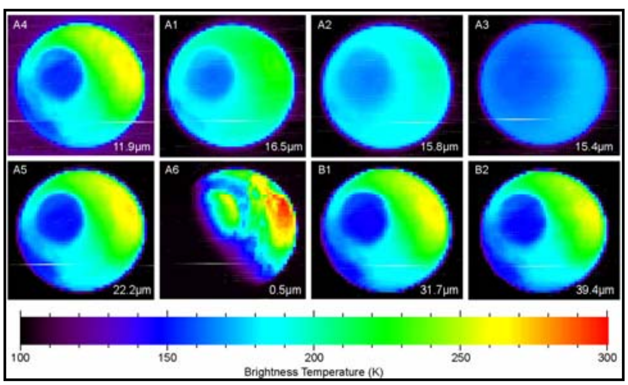

Figure 10: MCS Images acquired during Aerobraking Support Demonstration

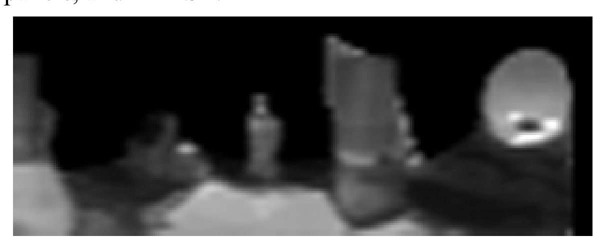

Figure 11: MCS Thermal Scan of MRO Nadir Deck

While there was a lot of work to prepare for these observations, there was a benefit to performing them. A slight error was found in the algorithm controlling the smear compensation of the spacecraft while it was nadir-pointed. The error was highlighted as a result of the non-standard conditions under which the images were acquired. The MRO spacecraft and its payload were designed to operate at an altitude of approximately 300 km with a ground relative velocity of about 3 km/s. However, since these observations occurred in the capture orbit, the orbital parameters were slightly different than what would be encountered in the Primary Science Orbit (PSO). The point in the capture orbit that corresponded to the ground speed of the PSO occurred at a higher altitude, making the error more noticeable.

Another benefit of the post-MOI images was the insight gained into how the MCS instrument affected the quality of the high resolution images taken by HiRISE. The normal scan pattern for MCS did create smearing in high resolution imaging, as expected, which proved the need for implementing a fix to the ITL which would pause MCS motion during high-stability observations.

Since these observations were performed so far ahead of the start of the Primary Science Phase, there was plenty of time to make the necessary corrections. A post-MOI HiRISE calibration image is shown in Figure 9, and the MCS demonstration images are shown in Figure 10.

C. Transition Phase Calibrations

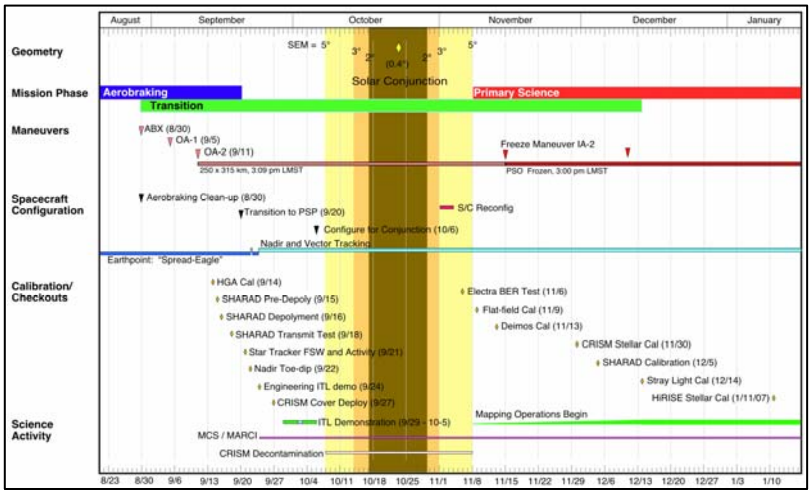

Figure 12: MRO Transition Phase Schedule

Aside from once again being in a situation with too many activities planned with little schedule margin, there weren't many new challenges left to be overcome in the Transition Phase. Though there were a few first time events taking place during this phase like the SHARAD Deployment and the CRISM Cover Deployment, there were adequate examples from previous activities that could be used as a starting point for new activities like the Primary Science Phase Stellar Calibration or the Flat Field Calibration.

The most difficult calibration to implement during this phase was the SHARAD Antenna Characterization. In this calibration, 55 observations were performed in 5 different spacecraft configurations. Although technically this calibration was performed within the boundaries of the Primary Science Phase, it is still considered a Transition Phase Calibration because it was originally slated to take place during Transition. Part of the reason for delaying this activity was to give the Flight Team a chance to recover from the rigors of Aerobraking and other activities needed for the Primary Science Phase. The other reason for the delay was that the performance of the SHARAD instrument following its deployment was so consistent with predicted values that it was no longer a high priority to characterize the antenna before proceeding with data taking.

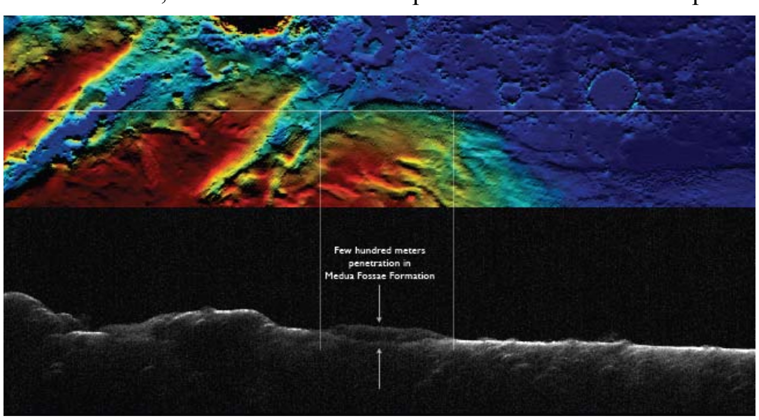

Figure 13: Post-SHARAD Antenna Deployment Image

VI. Conclusion

Substantial effort went into fully characterizing the in-flight performance of the MRO science payload prior to the start of the Primary Science Phase. These calibrations provided the science teams with actual operations experience and a better understanding of their instruments.

The results have been easy to recognize through the high quality of images that have been returned to date with little if no reprocessing has been necessary. As of the middle of July 2007, the total amount of data return has exceeded 16 Terabits of data.

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