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MARS RECONNAISSANCE ORBITER OPERATIONAL AEROBRAKING PHASE ASSESSMENT

**Jill L. Prince
Scott A. Striepe**

*NASA Langley Research Center,
Hampton, Virginia*

The Mars Reconnaissance Orbiter (MRO) was inserted into orbit around Mars on March 10, 2005. After a brief delay, it began the process of aerobraking – using the atmospheric drag on the vehicle to reduce orbital period. The aerobraking phase lasted approximately 5 months (April 4 to August 30, 2006), during which teams from the Jet Propulsion Laboratory, Lockheed Martin Space Systems Corporation, and NASA Langley Research Center worked together to monitor and maneuver the spacecraft such that thermal margin on the solar arrays was maintained while schedule margin was upheld to provide a final local mean solar time (LMST) at ascending node of 3:00pm on the final aerobraking orbit. This paper will focus on the contribution of the flight mechanics team at NASA Langley Research Center (LaRC) during the aerobraking phase of the MRO mission.

INTRODUCTION

Aerobraking has been used successfully for the three most recent Mars-orbiting spacecraft to reduce orbital size from large elliptical to smaller final science orbit. Most recently, aerobraking was applied to the Mars Reconnaissance Orbiter (MRO) from April to August 2006.^{1,2} During the aerobraking phase, the orbital period of the spacecraft was reduced from a 35 hour orbit to approximately 2 hours. This reduction was accomplished by using the solar panels of the spacecraft as a drag surface and flying through the upper atmosphere repeatedly, reducing orbital energy and eccentricity. The aerobraking phase of MRO was five months long, during which the Navigation Team at the Jet Propulsion Laboratory commanded the spacecraft and worked 24 hours per day to successfully maintain aerobraking schedule and thermal margin.^{3,4} The teams at NASA Langley Research Center assisted throughout aerobraking providing aerodynamics, thermal, and flight mechanics expertise. The efforts of the LaRC flight mechanics team is the focused of this paper.

MRO OVERVIEW

MRO is the largest spacecraft to orbit Mars to date with a 37.5 m² drag area, 13.6m wingspan, and pre-aerobraking mass of approximately 1400kg. Figure 1 shows MRO in the aerobraking configuration. It was designed to aerobrake for six months

before transition to the final primary science sun-synchronous orbit of 320km x 225km, the lowest altitude orbiter currently about Mars.

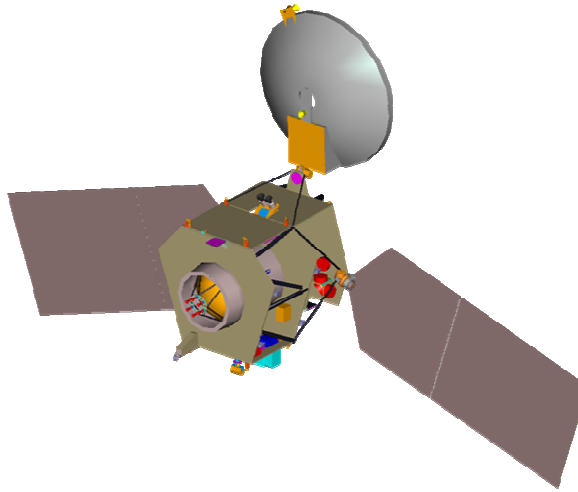


Figure 1. MRO in aerobraking configuration.

POST2 TRAJECTORY SIMULATION

The Program to Optimize Simulated Trajectories II (POST2) was used for all MRO trajectory flight simulations at LaRC. POST2 and its predecessor, POST, have vast heritage with similar applications including Mars Global Surveyor⁵ and Mars Odyssey.⁶ POST2 was used to integrate the equations of motion for the complete aerobraking trajectory and subsets of that mission trajectory using a fixed step 4th order Runge-Kutta integrator within the atmosphere and a variable step Krogh integrator for exoatmospheric propagation. An aerodynamic database was developed at LaRC for use within the trajectory simulation. This database provided force and moment coefficients for a range of spacecraft angle of attack, sideslip angle, and atmospheric density. This database was created using a Direct Simulation Monte Carlo (DSMC) computational fluid dynamics technique.

All POST2 simulations used Mars-GRAM 2005 MRO edition for the Mars atmosphere model. This engineering model does not accurately predict the highly variable density profiles for each orbit.⁷ To compensate for this operationally, atmospheric wave models were identified based on prior MRO drag pass data and used to predict ahead as long as one week.⁴ Wave models were typically not used in entire mission runouts since they did not hold for many days at a time. Reconstructed density values for comparison purposes were obtained by the NIA accelerometer team atmosphere reconstruction.⁸ This group was also responsible for spacecraft data formatting and output necessary for use by the flight mechanics team.

Simulations typically began from apoapsis data obtained from Orbit Propagation Timing Geometry (OPTG) files generated by the JPL Navigation team and formatted for POST2 use by the NIA accelerometer team. Trajectory simulations of the entire aerobraking phase of the mission (or mission runouts) completed before the start of

aerobraking verified the designed initial phase of aerobraking, called walk-in, that slowly lowered the periapsis altitudes until the sensible atmosphere is reached. Once within the desired periapsis heat rate limits (the heat rate corridor), maneuver logic within the simulation determined the necessity and required size of propulsive maneuvers at apoapsis (or ABMs) to maintain spacecraft heating within that corridor. More discussion of heat rate corridor control is detailed below.

Many Mars and MRO-specific models were incorporated into the POST2 simulation for trajectory analysis. The gravity model used was the MGS85F2 85 x 85 gravity field truncated to a 20 x 20 model to increase processing speed without sacrificing noticeable accuracy. The third-body solar gravitational perturbations were included as well. Solar radiation pressure models were available in the simulation but not used during aerobraking operations.

One of the most beneficial contributions of the LaRC flight mechanics team was the ability to produce quick predictions of the entire aerobraking phase. Subroutines were written for POST2 to allow automated mission runouts such that optimal propulsive maneuvers were chosen to remain within the desired heat rate corridor. Therefore, internally, the trajectory simulation would determine the magnitude and direction of an apoapsis maneuver to maintain MRO within the desired corridor. No human interaction was involved once a mission runout was started. This capability provided quick and accurate solutions to trades that would arise quickly.

LANGLEY MRO TRAJECTORY ANALYSIS

The main objective of the Langley flight mechanics team was to provide assessment of the MRO trajectory during the aerobraking phase. This assessment was provided in many stages: pre-aerobraking, daily operations, and weekly operations. Prior to aerobraking operations, a baseline reference trajectory was designed by the JPL Navigation team. Langley provided independent validation and verification of this baseline as well as trade studies on divergence from this baseline. During aerobraking operations, weekly assessments of the status of MRO with respect to the baseline were determined and trade studies on changes to the baseline were performed. On a daily basis, analysis was presented to the JPL Navigation team and recommendations were made on corridor control maneuvers.

Pre-Aerobraking Trade Studies

The aerobraking phase was designed such that the final local mean solar time (LMST) at ascending node was 3:00 pm. This decision determined the duration of the aerobraking phase such that a desired thermal margin could be maintained. The thermal margin was determined to be a percentage difference from a project defined thermal limit line found in the Environmental Reference Document and termed the ERD line. This ERD line was a temperature limit that captured the qualifying temperature limitations of all spacecraft components. For the majority of aerobraking, the solar panels were the

thermally limiting spacecraft component – later in the aerobraking phase, the onboard batteries were more limiting. The temperature limit was translated into a heat rate limit for simulation purposes and verified and validated by the Langley thermal team. The LaRC thermal team tracked this limit line and provided temperature estimates on the solar panel throughout the course of the aerobraking phase.

The project decided upon an aerobraking design that targeted 3:15 pm LMST for the first few months of aerobraking, hence starting aerobraking slightly more aggressively then backing off after the orbital period decreased to less than five hours. After sufficient schedule margin was achieved at this five-hour orbital period, the design called for a reduction in heat rate corridor and increase of thermal margin to complete the aerobraking phase. This JPL Navigation team design was independently validated by LaRC and is shown in figure 2.

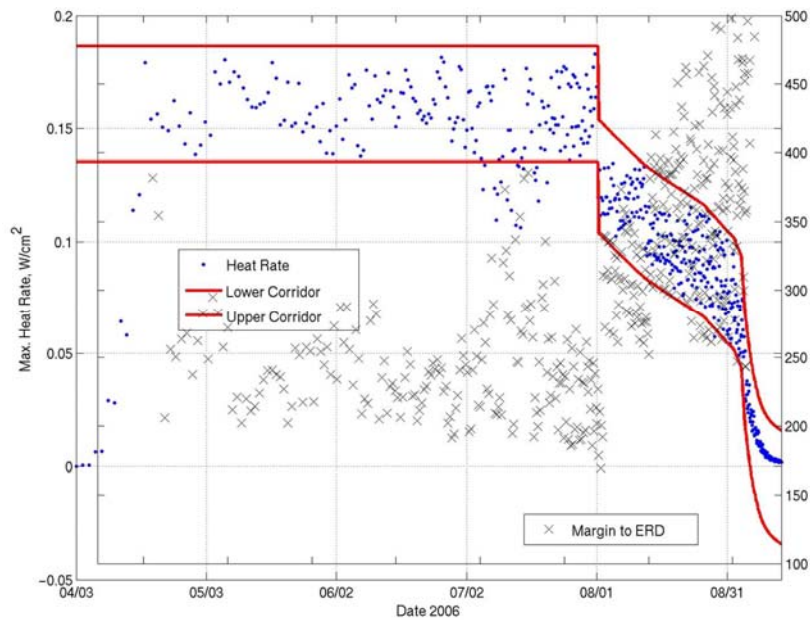


Figure 2. LaRC analysis of aerobraking reference trajectory before start of aerobraking phase.

Several trade studies on the aerobraking reference baseline were performed prior to the beginning of aerobraking. Some of these trades, such as pop-up analysis and decreased margin trades⁹ are found in reference 9 and will not be discussed further here. Immediately prior to the start of aerobraking, additional trade studies were performed due to the MRO project manager’s desire to delay the start of aerobraking. LaRC performed this trade study to determine how much of a post-MOI pre-aerobraking delay would be allowed while maintaining thermal margin on the solar panels and completing aerobraking by the final desired local mean solar time. This delay was determined to be 42 days if a minimum 150% margin was desired throughout the remainder of the aerobraking phase as shown in Fig. 3.

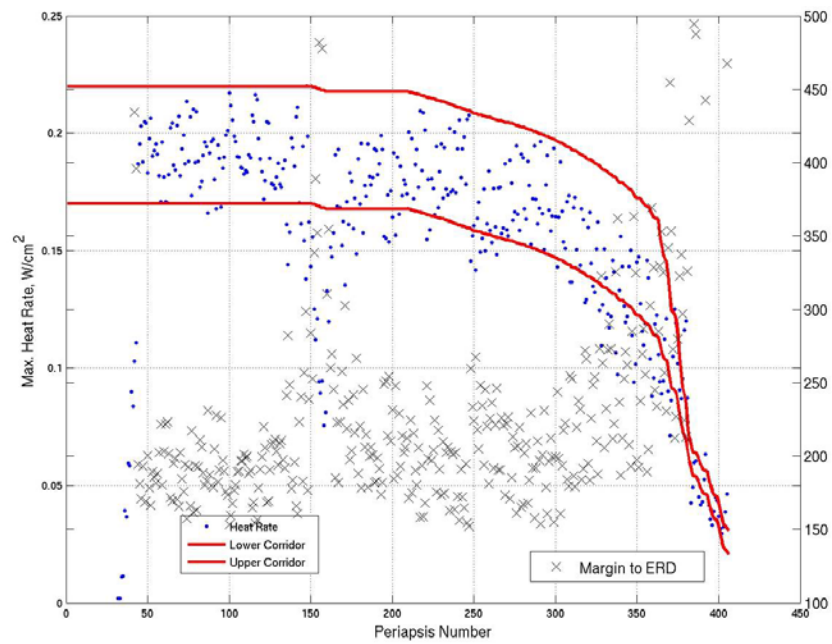


Figure 3. Analysis of delayed aerobraking schedule.

Based on this analysis and the desire to keep the thermal margin sufficiently larger than 150%, the actual delay chosen before beginning the operational aerobraking phase was approximately 10 days and MRO first began aerobraking on April 4.

During the aerobraking phase operations, the mission runout capability was again called upon to adjust the aerobraking design to complete aerobraking at a new local mean solar time target of 3:10. The LaRC analysis determined that a mean thermal margin for the second segment necessary to complete aerobraking at 3:10 was approximately 295% as shown in figure 4. The actual mean thermal margin during the second segment of aerobraking was approximately 280%. The actual final LMST was 3:10 pm.

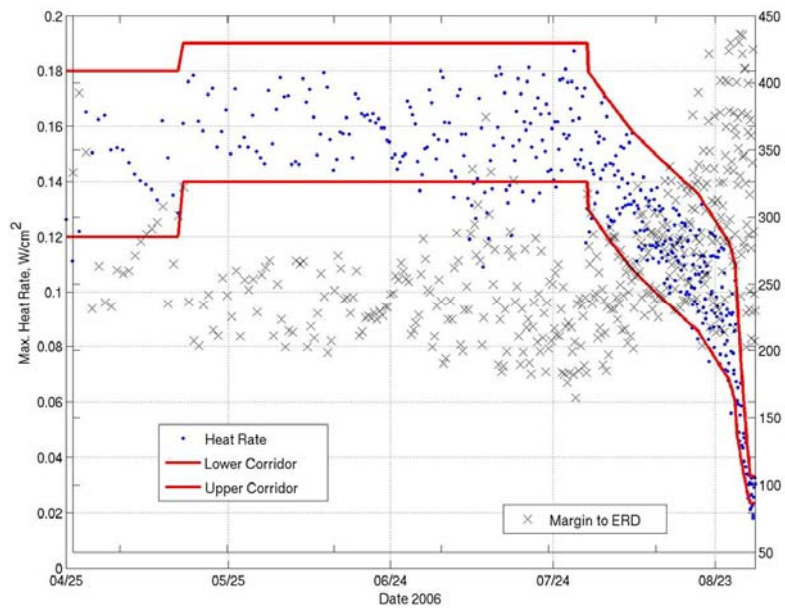


Figure 4. Analysis of increased schedule margin

Operations Weekly Analysis

The previously discussed mission runouts were used operationally as weekly LaRC products to the project. This capability was used to provide accurate predictions of the final local mean solar time at ascending node – allowing the project to determine whether MRO was ahead, behind, or on schedule.

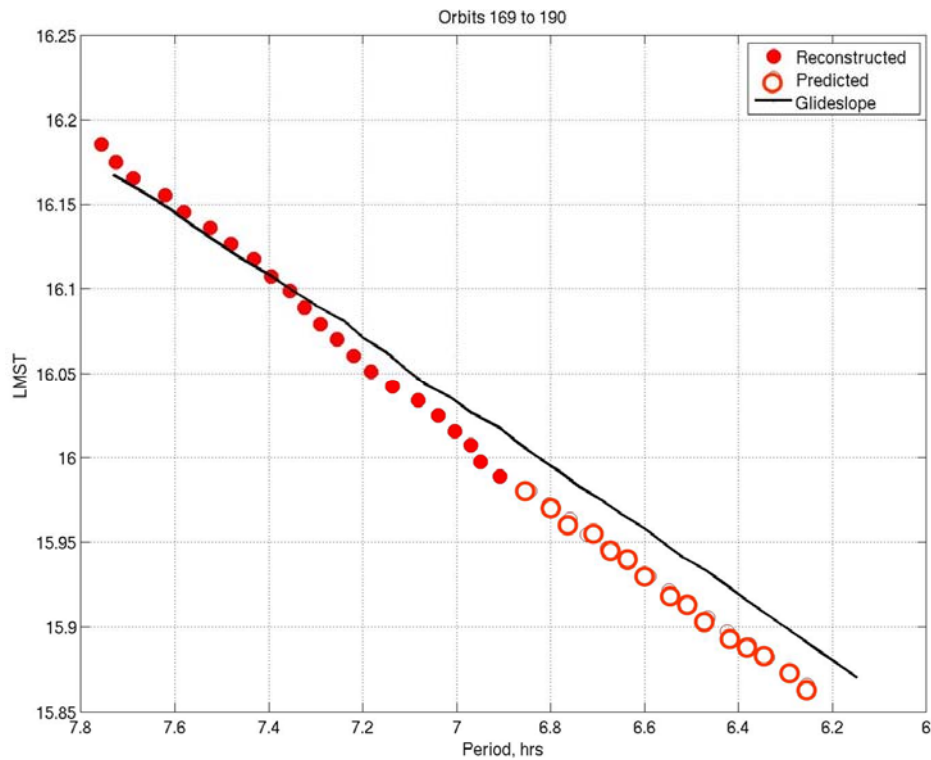


Figure 5. Reset 17 weekly analysis - glideslope comparison.

Figure 5 illustrates a weekly result example where MRO was slightly behind schedule. The solid red circles indicate reconstructed data points on a plot known as the glideslope. This glideslope is indicative of schedule, each red circle representing a single orbit's period versus the LMST at the ascending node. The solid black line indicates the original reference aerobraking baseline so that the red circles identify the current status with respect to the baseline. Red circles to the left of the glideslope identify orbits that are behind schedule, conversely red circles to the right of the glideslope indicate orbits that are ahead of schedule. In this plot, open red circles indicate predicted orbits. For this weekly analysis, this plot indicates that MRO was behind schedule with no indication of returning to the glideslope schedule without a down maneuver to raise the heating and reduce the orbital period more quickly.

In addition to the glideslope comparison, LaRC produced weekly projections from the current orbit predicting the final LMST at ascending node with the current defined corridor. From the same week's assessment shown in figure 5, the remainder of the aerobraking phase is predicted in figure 6. As indicated previously with the glideslope plot, again, this prediction shows that if the corridor remains the same, MRO would have completed aerobraking at 3:06, four minutes behind schedule.

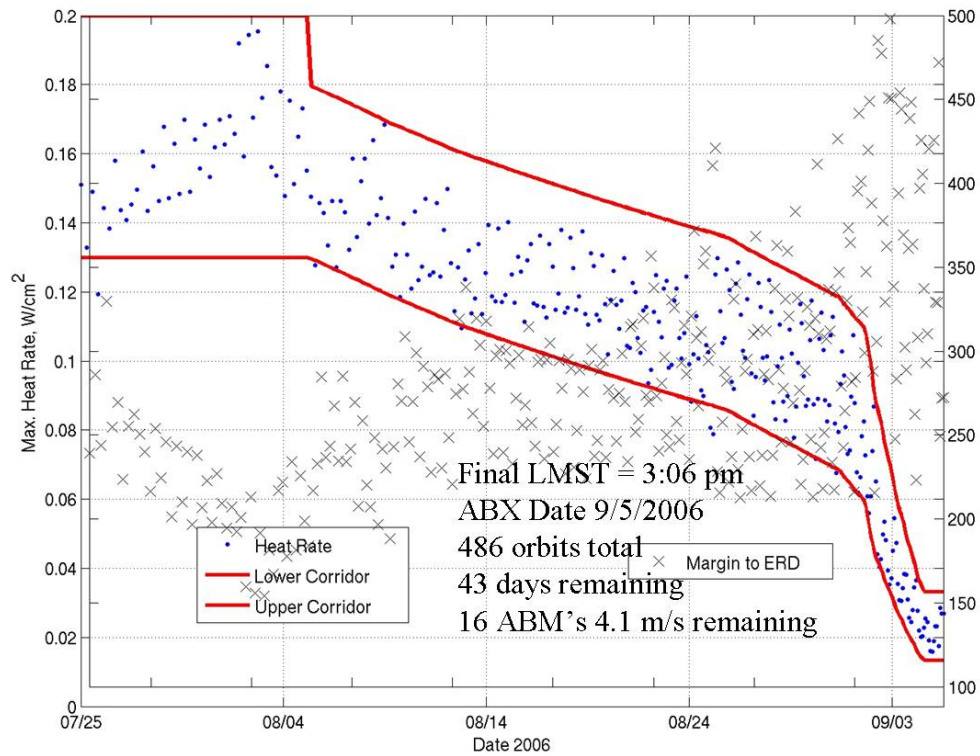


Figure 6. Reset 17 weekly analysis - mission runout.

Once it was determined that MRO was behind (or ahead of) schedule at a given week, a discussion was held on the corridor limits: whether there was a need to increase or decrease the current corridor based on the current schedule. The LaRC simulation has the capability to follow a near constant desired heat rate (essentially an extremely narrow corridor) for the entire mission. Although unrealistic in that a maneuver is necessary at every apoapsis to follow this path, it indicates what the final LMST would be if MRO flew about the middle of the corridor. On a weekly basis, LaRC produced this “constant” heat rate plot for three different trajectories: 1) if MRO flew directly in the middle of the current corridor; 2) if MRO averaged along the upper corridor; and 3) if MRO averaged about the bottom of the corridor. This analysis was done for two reasons. If MRO was severely behind (or ahead), this analysis might show that even if it had averaged at the top (or bottom) of the corridor, it might not have been able to catch up, i.e. significant changes to the corridor may be required. Secondly, this weekly analysis shows the flexibility of the corridor change from the beginning of aerobraking until the end of aerobraking. This study quantifies how more schedule margin may be gained with larger orbital periods than later in the aerobraking phase when schedule margin was tight and local mean solar time was more difficult to acquire. An example of this analysis is shown in figure 7.

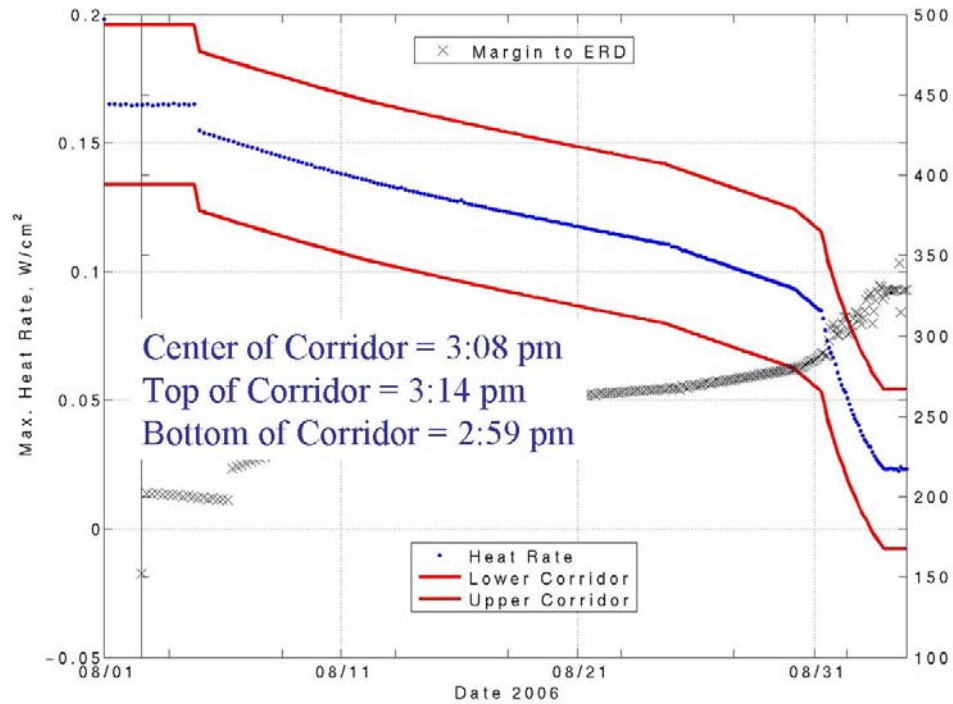


Figure 7. Reset 18 constant heat line analysis.

For this analysis, only the mid-corridor data are shown in the figure, although the results of the upper corridor and lower corridor are written in text, those data points resemble the corridor lines themselves. This figure, toward the end of aerobraking, indicates that the middle of the corridor line results in 3:08 pm final LMST with nine minutes on the lower end and six minutes on the higher end, i.e. 15 minutes of flexibility within the corridor. This same analysis performed at the beginning of aerobraking showed over an hour and a half of flexibility within the corridor – quantifying what the aerobraking operations team was already aware of – schedule margin is easier to obtain at the beginning of the aerobraking phase when the orbital periods are larger.

Operations Daily Analysis

Daily operational products were delivered to make decisions on whether or not an ABM would be performed, and if so – what magnitude, direction and orbit number that ABM would take place. If the nominal daily trajectory threatened the corridor limit or schedule requirements, LaRC would perform an ABM sweep of potential maneuvers to determine the most beneficial outcome. Options within the ABM sweep were usually restricted to those within that week’s desired ABM menu. An example of a daily ABM sweep is shown in figures 8 and 9. Here it was determined that a 0.402 m/s maneuver to lower periapsis (or down maneuver) was desired as it did not nominally violate the corridor and at this point, MRO was ahead of schedule and a 0.31 m/s down maneuver would put it back on the glideslope.

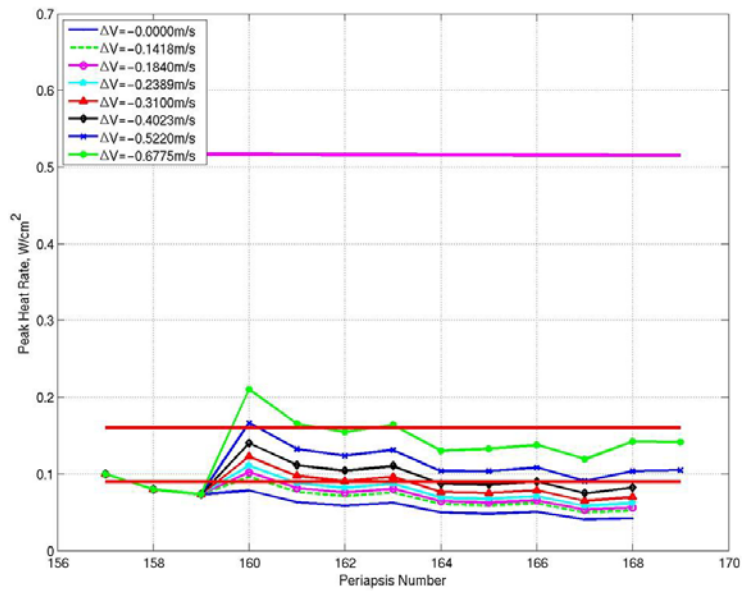


Figure 8. Daily ABM sweep heat rate results.

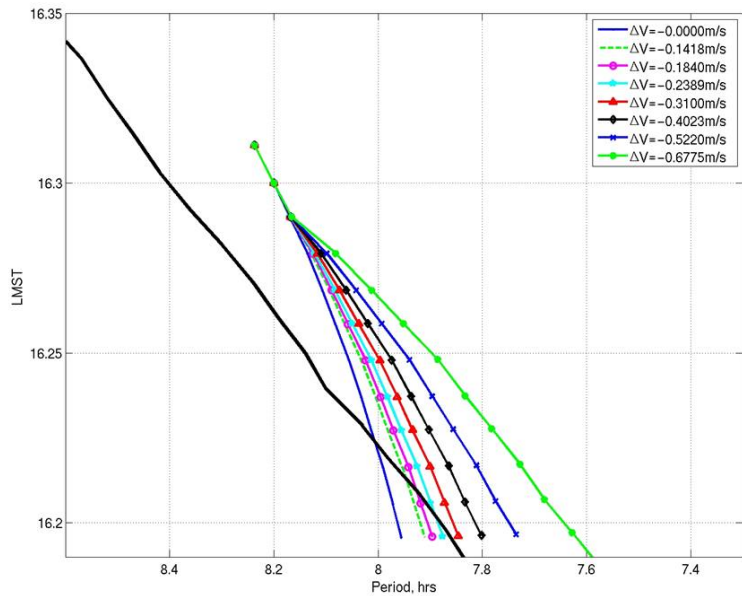


Figure 9. Daily ABM sweep glideslope results.

A unique aspect of LaRC aerobraking operations was the capability to produce Monte Carlo statistical predictions for MRO. A prediction was created for a trajectory extending several days ahead, and then random dispersions were applied to produce a statistical boundary of probabilistic cases. The 99% high and low indicators on the current trajectory were provided alongside the thermal limit line, as shown in figure 10.

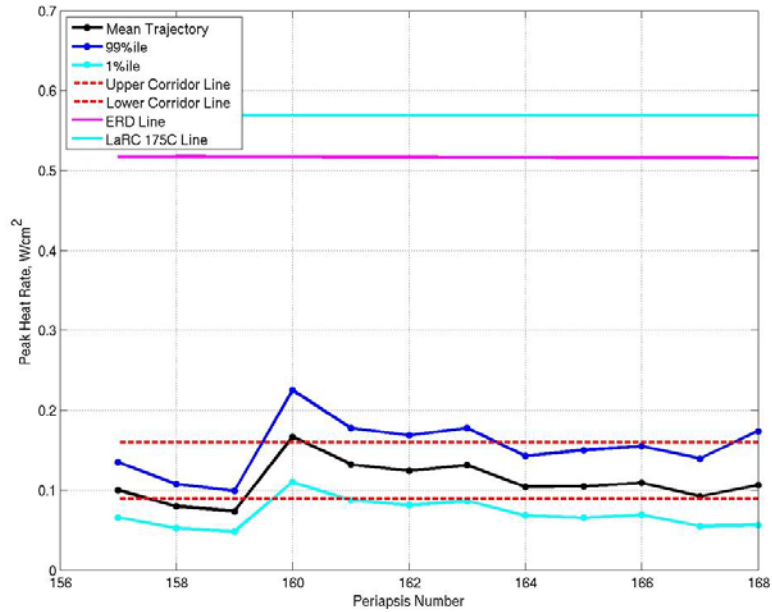


Figure 10. Daily Monte Carlo assessment of potential maneuver

This prediction was useful in estimating the risk of forcing an immediate, unscheduled maneuver as well as estimating the potential effects of future apoapsis maneuvers. The Monte Carlo assessment of the heat rate is shown in figure 10, whereas the schedule-keeping with respect to the glideslope is shown in figure 11.

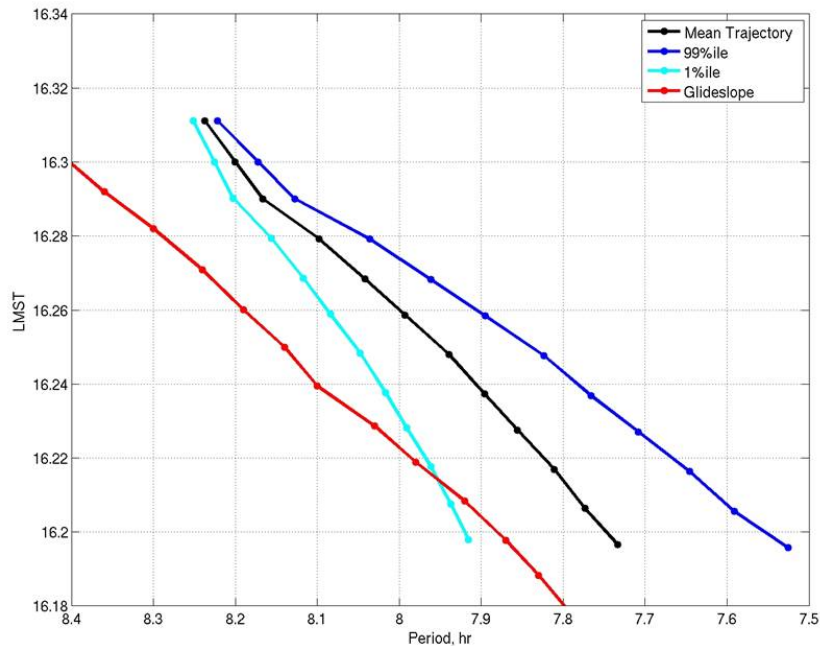


Figure 11. Monte Carlo assessment of potential maneuver and effect on glideslope

The uncertainties in the atmosphere, aerodynamics, and pointing angle at which apoapsis maneuvers are applied were used in the Monte Carlo analysis. The largest uncertainty was applied to atmospheric density. The MarsGRAM 2005 atmospheric model was used

in all POST2 simulations. The atmospheric densities experienced during MRO aerobraking operations were generally larger than the expected MarsGRAM densities. To model the atmosphere more accurately during operations, density multipliers were used in the simulation. The uncertainty applied to the atmosphere was merely a percentage of the multiplier used. The original multiplier uncertainty applied was 1.0. As the mission progressed, more atmosphere variability was experienced and the multiplier uncertainty value increased to 1.8 (e.g. density multiplier = 4.0 +/- 1.8). After MRO periapsis crossed the southern pole of Mars, the density multiplier began to decrease. When it decreased to below 2, a different method of applying uncertainties was necessary since MarsGRAM will not process density multipliers less than 0.1. Once this boundary was crossed, the atmospheric uncertainty was applied to the variable ZOFFSET, the altitude lookup variable through which densities are obtained. This change effectively forced Mars-GRAM to look up values at the spacecraft's current altitude adjusted by the ZOFFSET amount.

Final Aerobraking Assessment

MRO aerobraking was successful in obtaining a final LMST at ascending node of 3:10pm and completing aerobraking on August 31, 2006. Aerobraking was accomplished using 26 ABMs in the 145 days of aerobraking. The Monte Carlo analysis predicted the MRO trajectory well – 5 periapsis values after the first 25 orbits fell above the 99% high prediction range – the predictions versus actual values are shown in figure 12. It is noted that the uncertainty levels increased after approximately orbit 200, where the project began to use MRO mission data to determine the levels of atmospheric uncertainties based on MRO orbit data. Using actual mission data increased the expected level of uncertainty from 100% of the multiplier used in MarsGRAM to 180%. This increase allowed the simulation to capture most of the remaining outlier max densities throughout the rest of the aerobraking mission.

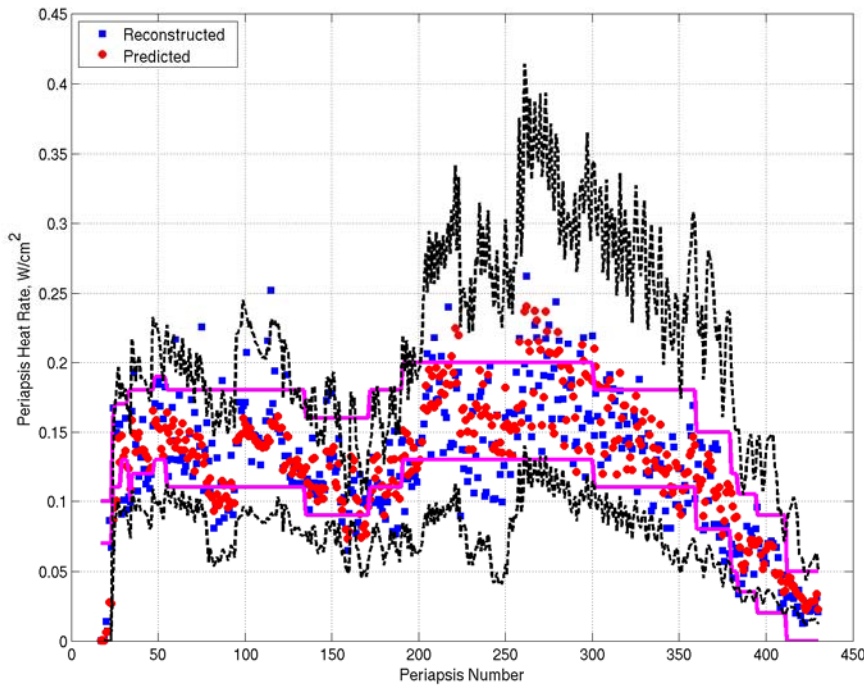


Figure 12. Operational corridor with Monte Carlo predictions vs reconstructed orbital heating

SUMMARY

The LaRC flight mechanics team provided analysis on daily apoapsis propulsive maneuver decisions and weekly spacecraft status reports throughout the five month aerobraking phase. The aerobraking phase was completed by the successful aerobraking termination maneuver on Aug 30, 2006. MRO is currently on schedule to examine the Martian surface and sub-surface through 2008.

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NOTATION

ABM	aerobraking maneuver
ERD	Environmental Reference Document
JPL	Jet Propulsion Laboratory

LaRC	NASA Langley Research Center
LMST	local mean solar time
MRO	Mars Reconnaissance Orbiter
NIA	National Institute of Aerospace
OPTG	Orbit Propagation Timing Geometry
POST2	Program to Optimize Simulated Trajectories II

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