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2001 Mars Odyssey Aerobraking

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The Mars Odyssey spacecraft was inserted into a highly elliptical capture orbit about Mars on 24 October 2001. To establish the required science mapping orbit, the propulsive capabilities of the spacecraft were supplemented by aerobraking. The necessary orbital period reduction was achieved by 332 successive aerobraking drag passes over a 76-day time period. The strategy, implementation, and results of the aerobraking phase of the mission are detailed. Aerobraking subphases, constraints, modeling, maneuver logic, trajectory characteristics, and key decisions are described. Differences between Odyssey and the Mars Global Surveyor aerobraking experiences are included.

Introduction

THE 2001 Mars Odyssey spacecraft was launched 7 April 2001 aboard a Boeing Delta 2 7925 launch vehicle from Cape Canaveral Air Station in Florida. After a 7-month interplanetary cruise, the spacecraft was propulsively inserted into a highly elliptical, 18.6-h period, capture orbit about Mars on 24 October 2001. The Mars Odyssey orbiter carries scientific payloads that will determine surface mineralogy and morphology, conduct global gamma-ray observations to determine the elemental composition of the surface and shallow subsurface, and study the Mars radiation environment from orbit.

The science instrumentation was designed to operate in a low-altitude, near-sun-synchronous, near-circular-science-mapping orbit with a period of just under 2 h. Following the propulsive insertion into an 18.6-h period orbit, aerobraking was used to reduce the period. Achieving this reduction via aerobraking reduced the size of the orbit insertion burn, which in turn reduced the required propellant load enabling the use of the Delta 2 class launch vehicle. During the 11-week aerobraking phase, the cumulative drag force provided the equivalent of a 1.08 km/s ΔV. As described in this paper, Odyssey aerobraking marked a return to the proven aerobraking techniques used by the Mars Global Surveyor (MGS) spacecraft in 1997 (Refs. 1–4). This paper discusses the strategy, implementation, and results of the aerobraking phase.

Aerobraking is accomplished by lowering the periapsis altitude of the orbit into the upper reaches of the atmosphere, utilizing the atmospheric drag force to reduce orbital energy. As orbital energy is reduced, the spacecraft's orbit period decreases and the apoapsis is lowered. During an aerobraking pass, atmospheric friction leads to heating of the spacecraft; therefore, the primary limitation to the reduction in period per drag pass is the spacecraft thermal limitation. Periapsis altitude, and, thus, heat rate, is controlled by maneuvers at apoapsis. For Odyssey, the timing and magnitude of these maneuvers were determined by a daily process involving the navigation team, the Atmospheric Advisory Group (AAG), the spacecraft team, and the Project management.

The variability of the Martian atmosphere and the intricate slate of spacecraft activities that must be performed during each aerobraking orbit make aerobraking the most demanding part of the Odyssey mission. Aerobraking was successfully completed on 11 January 2002 and was terminated by a propulsive maneuver that raised periapsis altitude out of the atmosphere. Four additional propulsive maneuvers were used to attain the final science mapping orbit.

The primary science mission began on 19 February 2002 and extends for 917 days. During this time, the orbiter will also serve as a communications relay for future landers. The relay capability will continue for an additional 457 days following completion of the science mission for a total prime mission duration of two Mars years (1374 days). Nothing in the design or operations precludes an extended science mission.

Note that in this paper, all values of local true solar time (LTST) and local mean solar time (LMST) are referenced to the descending equator crossing of the orbit.

Overview

Orbit Insertion

Mars orbit insertion (MOI) was performed by using a mixture of oxidizer and fuel until the oxidizer was exhausted. Unlike the MGS mission, which employed accelerometers to terminate main engine cutoff to achieve a single post-MOI period, Odyssey used accelerometers during MOI to detect oxidizer depletion. The uncertainty associated with Odyssey's mode of MOI execution resulted in a range of possible post-MOI periods with a predicted mean of 19.7 h and 1-σ variation of 1.7 h. Accommodating this range complicated aerobraking planning, but the use of all onboard oxidizer provided the opportunity for a smaller period than would have been achieved with a traditional accelerometer or timer cutoff.

If the post-MOI orbit period had exceeded 22 h, a propulsive maneuver would have been performed to ensure that aerobraking could be completed before power-related constraints were violated. The actual post-MOI period of 18.6 h was about 0.7-σ lower than the mean and significantly below the 22-h limit negating the need for further propulsive period reduction.

Spacecraft Configuration

The spacecraft in the aerobraking configuration is shown in Fig. 1. Shortly before a drag pass, the solar array was stowed such that the combined frontal area was 11 m^2, and the spacecraft was placed in the proper drag pass orientation as shown in Fig. 1. After the drag pass, the solar array was deployed for maximum power collection, and spacecraft telemetry was transmitted to Earth. The spacecraft mass at the start of aerobraking was 461 kg.

Aerobraking Phases

Aerobraking was subdivided into four distinct phases in both design and operations: walkin, main phase, endgame, and walkout. Main phase was further subdivided into two parts, main phase 1 and main phase 2.

Aerobraking was initiated with the walkin phase. During walkin, the spacecraft periapsis altitude was gradually lowered from the post-MOI altitude of 292 km to 111 km. This phase accomplished

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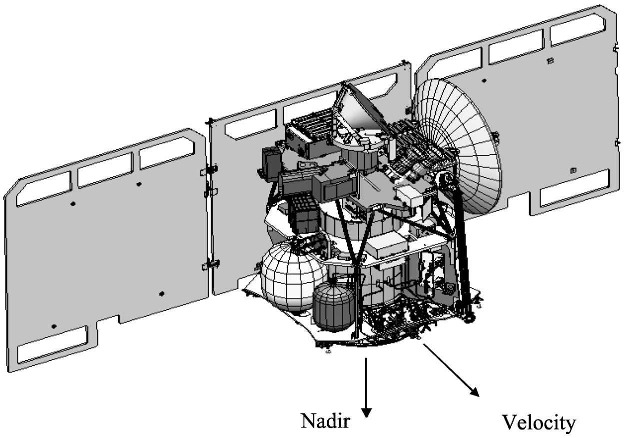

Fig. 1 Spacecraft in aerobraking configuration.

several objectives, including initiating contact with the Martian atmosphere, initiating calibration of several design and analysis models, and evaluating spacecraft and flight team performance before the use of sustained main phase heat rates.

The majority of aerobraking was accomplished during main phase and endgame. During this time period, the driving constraint was the thermal limitation of the spacecraft solar array. The general strategy was to obtain as much period reduction per pass as possible while still maintaining adequate margins against thermal limitations of the spacecraft. The maximum heat rates targeted were chosen to be significantly lower than the spacecraft thermal limits to accommodate the unpredictability of the atmospheric density. In main phase, the thermal limit was driven by peak heat rate, whereas during endgame the thermal limit was driven by integrated (cumulative) heating. The design and operational strategy was the same for both phases.

Once the predicted mean orbit lifetime of the spacecraft reaches one day, the final phase of aerobraking, walkout, begins. Lifetime is defined as the time required for the spacecraft apoapsis altitude to decay to 300 km. At this altitude, the spacecraft is a short time away from spiraling into the planet and being lost. The one day lifetime was a programmatic constraint aimed at preventing mission failure in the event control of the spacecraft was lost during these final few days of aerobraking. During walkout, the orbital lifetime requirement is more restrictive than spacecraft thermal limitations, and periapsis altitude is gradually increased to maintain lifetime.

Aerobraking Constraints

The aerobraking process is subject to a number of constraints adopted to ensure the safety of the spacecraft and achievement of the proper science orbit. The overriding constraint was to protect the spacecraft from damage due to high temperatures resulting from atmospheric friction during an aerobraking pass.

Thermal Constraint

Thermal limits were expressed in terms of freestream heat rate indicator [Eq. (1)], rather than temperature because heat rate is a straightforward calculation for the navigation team and does not require thermal modeling. The most thermally sensitive component of the spacecraft during aerobraking was the solar array, which served as the primary source of drag area due to its size. The heat rate corresponding to the solar array maximum flight allowable temperature of 175°C determined the maximum heat rate limit for the spacecraft. The maximum heat rate varied with drag pass duration and was, therefore, specified as a function of apoapsis altitude by the thermal subsystem. Maximum heat rate usually occurred within a minute of periapsis and averaged about 8% higher in value than periapsis heat rate. Thus,

$$\text{heat rate indicator} = \tfrac{1}{2}\rho V_{\text{atm}}^3 \qquad (1)$$

where ρ is the atmospheric density and V_{atm} is the velocity with respect to atmosphere.

Predictions of future periapsis velocities, as well as altitudes, were highly accurate because the gravity field of Mars is known to great precision,[5] whereas predicting density is still quite difficult. Because the Odyssey aerobraking location and season (northern latitudes during northern winter) were not sampled during MGS aerobraking, and the Martian atmosphere is known to be highly variable and unpredictable with current models, a significant margin against the flight allowable heat rate was adopted. The thermal limits were used to construct a heat rate flight corridor whose maximum heat rate was nearly one-half the flight allowable thermal limit to accommodate unpredicted increases in density. The basic aerobraking strategy used maneuvers to maintain the predicted heat rate below the top of this corridor but above a lower limit to ensure the timely completion of aerobraking. Based on analysis of the MGS aerobraking experience, as well as predictions of the density variability anticipated for Odyssey, the AAG recommended that a heat rate margin of 80–100% with respect to the flight allowable maximum heat rate limit be maintained, and this strategy was adopted.

Maneuvers

Precession of the orbit due to oblateness alters the periapsis altitude. Thus, periodic maneuvers are required to maintain heat rate within the desired corridor. These maneuvers, called aerobrake trim maneuvers (ABMs), are performed at apoapsis to change periapsis altitude and, in turn, the atmospheric density.

Maneuver magnitudes were selected from a discrete preverified menu, which was updated weekly; however, a strategy that preselected all desired magnitudes before insertion may have provided sufficient flexibility with reduced workload. Burn directions were chosen from a set of quaternions validated before orbit insertion. In nominal operations, only two maneuver directions were used: up maneuvers raised periapsis altitude decreasing heat rate and down maneuvers lowered periapsis altitude increasing heat rate.

Only one maneuver was permitted per day, and maneuvers were generally only permitted on the last apoapsis of a command sequence to not perturb the existing sequence timing downstream should a maneuver be selected. The decision as to whether a maneuver was needed and, if so, what magnitude, formed the majority of the daily operations work conducted by the aerobrake planning and operations segment of the navigation team.

Power Constraint

In the design phase, it was known that the spacecraft battery state of charge and energy balance approached unacceptable limits for certain worst-case scenarios characterized by LTST of the descending equator crossing earlier than 1400 hrs. During aerobraking, the LTST decreases at an average rate of ~2 min per day due to the motion of Mars about the sun. As LTST decreases, solar occultation duration increases, reducing the power collection time to the arrays. A constraint was, therefore, imposed that the LTST of the descending equator crossing during aerobraking must be greater than 1400 hrs to 99% confidence to ensure adequate power to the spacecraft.

Period Reduction Maneuver

To complete aerobraking before LTST drifted earlier than the 1400 hrs power constraint, the maximum initial orbit period was required to be $\leq$22 h. If the post-MOI period had exceeded 22 h (10% probability), a propulsive period reduction maneuver (PRM) would have been performed three revolutions after MOI to reduce the orbit period to 20 h. The 2-h difference in the post-PRM target period (between the 22-h maximum and the 20-h targeted if a PRM would be executed) accounted for LTST drift during the additional three revolutions from MOI to PRM. Because the post-MOI period was 18.6 h, the PRM maneuver was not performed.

Dust Storm and Safe Mode Accommodation

An additional nine days of aerobraking duration margin was levied as a programmatic design constraint to provide margin against delays due to dust storms and/or safe mode entry(s) by the spacecraft. The primary strategy for reducing the risk due to either type of event is to raise periapsis altitude; however, this reduces the average drag and period reduction per pass (if aerobraking can continue at all).

The nine-day margin was the sum of a seven-day margin to cover the onset of a major regional or global dust storm (AAG estimate) plus a two-day margin for delay due to safe mode entry(s). Because these were highly unpredictable events and, therefore, somewhat difficult to model, this margin was allocated explicitly against the 1400 hrs constraint instead of being analyzed as a statistical quantity. The nine days are equivalent to 18 min LTST margin resulting in an effective 1418 hrs LTST constraint that was utilized for planning. During Odyssey aerobraking, no delays due to dust storms occurred, and a single safe-mode entry at the first drag pass increased aerobrake duration by $\sim$18 h.

Orbital Lifetime Constraint

The Odyssey orbital lifetime was constrained to be $\geq$1 day assuming a mean atmosphere. The definition of lifetime is the time required for apoapsis altitude to decay to 300 km (same as MGS definition[2]). Within a few revolutions of this geometry, the spacecraft will most likely reenter the Martian atmosphere and be lost. The lifetime constraint only becomes dominant during the walkout phase of aerobraking.

Because walkout was considered by the project to be the riskiest phase of aerobraking, a one-day lifetime was selected to minimize the number of drag passes while maintaining acceptable lifetime margin. The Odyssey lifetime requirement was one-half the two-day lifetime levied for MGS because the Odyssey spacecraft's recovery from anomalies was predicted to be much shorter than MGS for many failure scenarios. Also, unlike MGS, Odyssey had an autonomous popup capability that would autonomously raise periapsis altitude out of the sensible atmosphere if the spacecraft entered safe-mode for any reason.

During operations, the project also levied a requirement that the 99% low lifetime exceed 8 h to accommodate outages at a single Deep Space Network tracking station.

Propellant

A programmatic constraint required that sufficient propellant must exist to complete the two Mars year (1374 day) prime mission to 99% confidence level. To ensure compliance with this requirement, as well as permit certain mission trades, a ΔV Monte Carlo program was developed by the navigation team to statistically model all uses of propellant during aerobraking and the subsequent science mission.

Science Payload

Key instruments in the Odyssey science payload require specific solar orientations for optimal results. For aerobraking, these geometries were translated into the constraint specifying that, at the end of aerobraking, the LTST at the descending equator crossing must lie between 1400 and 1610 hrs with a preferred range from 1430 to 1530 hrs.

The lower LTST bound of 1400 hrs was dictated by power constraints but provided acceptable science return. The upper LTST bound of 1610 hrs was established solely to preserve favorable science conditions. Odyssey ended aerobraking at 1504 hrs LTST, in the middle of the desired range.

The more than 2-h Odyssey LTST range contrasts with the tight MGS mission requirement to achieve a postaerobraking LMST of 1400 hrs within $\pm$12 min (Ref. 3). Because most representative aerobraking trajectories, for a wide range of initial (post-MOI) periods, were predicted to finish within the required LTST range, no propellant was required for further period reductions except in the unlikely case of an initial orbit period $\geq$22 h. However, the design incorporating a range of initial orbit periods, rather than a single requirement, increased the need for trade studies and analysis to optimize parameters and constraints for all realistic scenarios.

Roles and Responsibilities

Aerobraking implementation required 24-h a day, 7-day a week operations at both the Jet Propulsion Laboratory (JPL) in Pasadena and Lockheed Martin Astronautics Operations in Denver. Additional teams throughout the United States supported daily operations including staff of the NASA Langley Research Center (LaRC) and George Washington University (GWU). Mars atmospheric scientists, and members of the MGS spacecraft and science teams, who provided atmospheric monitoring.

Thermal limitations of the spacecraft, expressed in terms of a heat rate indicator, were supplied by the spacecraft thermal subsystems team and were updated once during the mission. During aerobraking operations, continuous tracking coverage was allocated by the Deep Space Network. This coverage permitted a rapid assessment of spacecraft health after each drag pass by the spacecraft team and supported the demanding schedule of the navigation orbit determination process.[6]

To maintain heat rate within the desired heat rate corridor, daily maneuver decision meetings were held to determine if a maneuver was necessary and, if so, the magnitude and direction. Independent maneuver recommendations were supplied by the navigation team and the AAG composed primarily of Mars atmospheric scientists. During this meeting, these recommendations were reviewed by the spacecraft team, and a final decision was rendered by upper-level project management, usually the Mission Manager. The navigation and AAG teams usually previewed their respective recommendations during the daily AAG teleconference held before the daily maneuver decision meeting.

NASA LaRC played a significant role both in aerobraking design and operations in the areas of flight dynamics, aerodynamics, thermal analysis, and atmospheric trending.[7–9] A joint LaRC/GWU atmospheric modeling team[10] and members of the AAG provided a wealth of information on atmospheric trending during operations. The navigation team also independently trended the atmosphere and ultimately decided which model to use for navigation team maneuver and orbit determination work.

The AAG and members of the MGS science team performed daily monitoring for dust storms of sufficient size to pose a hazard to the spacecraft. Dust storms were of concern because the atmospheric density and, thus, heat rate could double within 48 h of the onset of a major regional or global dust storm.[2,3] Odyssey arrived near the peak dust storm season, and the biggest global dust storm seen on Mars in several decades was just clearing as Odyssey commenced aerobraking. Three instruments aboard the MGS spacecraft (Thermal Emission Spectrometer, Mars Orbiter Camera, and Mars Horizon Sensor Assembly) were dedicated during Odyssey aerobraking for comprehensive monitoring of storm activity. These data were then analyzed by atmospheric scientists and reported to the project on a daily basis.

Modeling

The dominant nonatmospheric models utilized during aerobraking included the JPL MGS75E gravity field[5] (through degree and order 55), the sun and planets as additional gravitational bodies, and solar radiation pressure. Because of the high accuracy of MGS75E, the dominant source of uncertainty was atmospheric modeling.

The MarsGRAM 3.7[11] atmosphere model was used for the initial aerobraking design until analysis determined that MarsGRAM 2000 model[12] (MG2K) better represented the expected atmosphere. For the same geometries, MG2K predicted lower scale heights than the older MarsGRAM 3.7 model, resulting in up to 35% less total drag per pass for the same maximum heat rate. To accommodate the new predictions, the aerobraking strategy was redesigned postlaunch using MG2K. The new strategy resulted in longer planned aerobrake duration, additional drag passes, and a modified PRM strategy.

Based on AAG recommendations, the MG2K dust opacity (parameter Dusttau) was set to 1.0 and the optional Bougher altitude offset (parameter Zoffset) (Ref. 12) was set to 5 km for all of the aerobraking. The MG2K parameter W scale was originally (incorrectly) set to the default value of 20 km. This was updated to an AAG recommended value of 1000 km at orbit 102, when the error was discovered through comparisons with independent LaRC analysis. The coefficient of drag was defined by a variable Cd model developed by the LaRC aerodynamics group.[8]

As noted in Refs. 1 and 4, MGS's development of Fourier series, or wave models, to model longitude-dependent atmospheric density

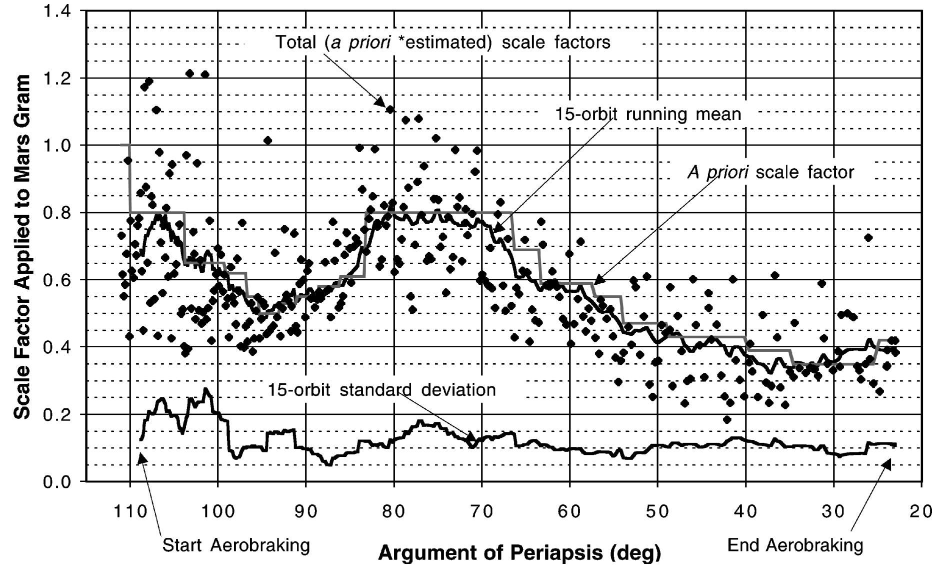

Fig. 2 Atmospheric model multiplier.

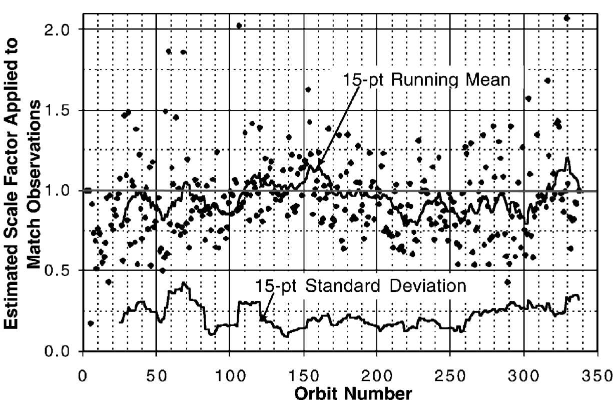

Fig. 3 Predictive capability.

variations significantly improved the predictions for that mission. A similar atmospheric trending and modeling effort was conducted daily on Odyssey with members of the flight team and the AAG evaluating many different models.[10] Although some of these models appeared to represent the observed data well for relatively short periods of time (up to a few days), the navigation team determined that no single wave model, or even wave format, could consistently predict future atmospheric behavior adequately for use in critical maneuver recommendations.

Although it was not possible to reliably predict the density for specific passes, applying a constant scale factor to the MG2K model improved the model's predictive capability. This adjusted model defined the nominal predictive model used by the navigation team. The scale factor (a priori scale factor in Fig. 2) was monitored daily and updated as necessary to reflect the average density observed in recent passes. For reconstructions, an additional scale factor was estimated to match the observation for each drag pass. The product of this estimated factor and the a priori value represents the total multiplier on MG2K that was required to match the observations. Total multiplier, associated 15-orbit running mean, and standard deviation based on 15-orbit samples are also in Fig 2. In general, MG2K overpredicted the magnitude of the density (indicated by scale factors less than one) but predicted the general shape of the density profile reasonably well.

The estimated scale factor applied to the nominal predictive model for each pass is plotted in Fig. 3. As the ratio of the observed periapsis density to the nominal value, this factor reflects the predictive capability of the model. For example, in Fig. 3, a value of 1 represents a perfect prediction; 2 indicates that the observed density was twice the predicted value. The standard deviation of these estimates indicates that the navigation model generally predicted the observed density within about 20–40%, 1-σ. In cases where larger deviations were observed (such as a scale factor of 2), the project maintained a rapid aerobraking maneuver capability that was available to protect the spacecraft in the event it was deemed necessary to react to this level of variability.

Much of the atmospheric variability that was observed in high-latitude regions is believed to be the result of a polar vortex. Because MGS did not aerobrake in the north polar region, nor during the northern winter season as did Odyssey, neither the effect nor the magnitude of this vortex was clearly understood before Odyssey's arrival at Mars. Information gained from passes through the vortex boundary in early aerobraking was helpful in understanding the density observed in this region in main phase 2; however, at least 100% heat rate margin was maintained, including the second encounter with the vortex boundary region in phase 2 because the atmosphere still could not be predicted reliably.

Aerobraking Profile Characteristics

Heat rates reconstructed from each drag pass, as well as the constraining limits, are shown in Fig 4. As expected, actual heat rates sometimes exceeded the upper limit of the heat rate flight corridor due to atmospheric variability. The characteristics of each aerobraking phase are summarized in Table 1, which also includes a comparison with MGS aerobraking data.[3]

In 76 days, 332 consecutive drag passes reduced the orbital period from 18.6 to 1.9 h. The equivalent total ΔV provided by aerobraking was 1.08 km/s. To control heat rate, the spacecraft executed 33 ABMs, expending a total ΔV of 46.6 m/s (including the final maneuver to raise periapsis out of the atmosphere).

The heat rate indicator limits defined in Fig. 4 were specified by the thermal subsystem based on the predicted equivalent temperature profile corresponding to a given density profile and orbital geometry. The limits early in aerobraking are dominated by peak heating considerations. Heat rate limits decline in the endgame phase because integrated heating eventually dominates the peak heating concerns. Heat rate declines even more sharply during the final walk-out phase to maintain a mean orbit lifetime of one day. The increased flight allowable thermal limit near orbit 75 was the result of the thermal subsystem's adoption of the MG2K atmosphere model for converting temperatures to heat rate after reviewing the flight data.

Given the higher than anticipated variability observed in early main phase, the project chose to maintain 100% thermal margin throughout most of main phase, even though the design planned to switch to 80% margin within 10–15 orbits after the end of walkin. Less margin (70–80%) was utilized for a few days near the north pole (orbits 80–105) given the low-density variability observed (as

Table 1 Odyssey aerobraking characteristics and MGS comparison

	Walkin	Main phase and endgame: Main phase 1	Main phase 2	Endgame	Walkout	Odyssey, all phases	MGS, all phases
Date range	27 Oct. 2001–6 Nov. 2001	6 Oct. 2001–18 Dec. 2001	18 Dec. 2001–25 Dec. 2001	26 Dec. 2001–3 Jan. 2002	3 Jan. 2002–11 Jan. 2002	27 Oct. 2001–11 Jan. 2002	15 Sept. 1997–4 Feb. 1999
Duration, days	9.9	41.8	7.2	8.7	7.4	76.1	299
Orbit range (total orbits)	5–18 (14)	19–126 (108)	127–171 (45)	172–248 (77)	249–336 (88)	5–336 (332)	4–1292 (891)
Altitude range, km	111–158	95–111	96–102	100–111	107–119	95–158	100–149
Period range, h	17.3–18.5	4.7–17.1	3.4–4.7	2.3–3.4	1.9–2.3	1.9–18.5	1.7–45.1
Median heat rate, W/cm^2	0.05	0.24	0.20	0.13	0.04	0.16	0.07
LTST at end subphase, hrs	1715	1530	1516	1505	1504	1504	0219
No. of maneuvers	7	11	2	5	8	33	92

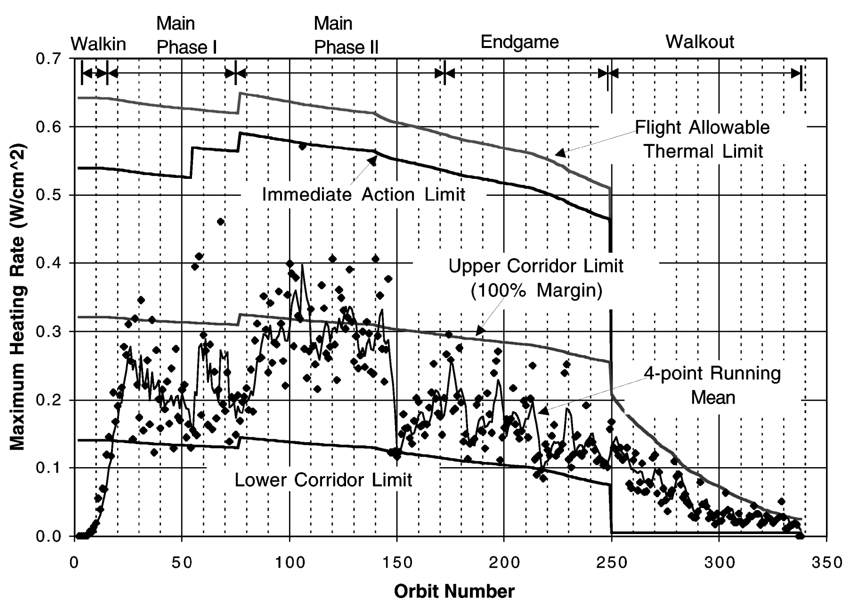

Fig. 4 Maximum heat rate.

evidenced by the significantly reduced standard deviation in Fig. 2). The higher average heat rates for these orbits contributed significantly to Odyssey's ability to finish aerobraking ahead of schedule. However, following an unusually high density at pass 106 (estimated scale factor >2), the 100% margin constraint was reimposed and maintained until walkout. For the remainder of main phase and endgame, the 100% margin was usually applied to a four-point running mean of heat rate, which meant that heat rate predictions for individual passes could exceed the 100% margin corridor.

If, after any aerobraking pass, the thermal subsystem determination of heat rate based on thermocouple sensor data exceeded the immediate action heat rate (Fig. 4), a maneuver would have been commanded by the ground system as soon as possible to raise altitude and reduce heat rate. The purpose of the immediate action limit is to force corrective action when heat rate approaches the flight allowable rather than waiting until heat rate exceeds flight allowable.

Early in aerobraking, the immediate action limit was defined as 16% margin with respect to the flight allowable heat rate limit. At orbit 55, the project reduced the immediate action limit to 9% of the flight allowable limit based on better than expected thermal predictions. The immediate action limit was also increased to reflect its definition as a percentage of the flight allowable when the flight allowable was updated near orbit 75.

The sharp decrease in the heat rates near orbit 150 is the result of the project's decision to perform a relatively large maneuver to raise periapsis before the December holidays to reduce the workload and the criticality of daily monitoring and maneuver decisions over the holidays. However, all teams continued to monitor and report the status of the ongoing aerobraking during this time.

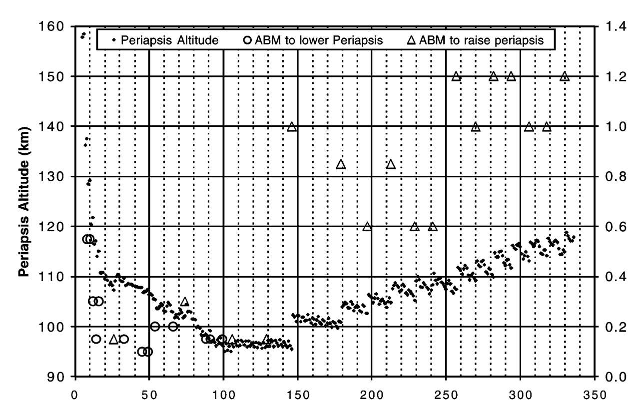

Fig. 5 Periapsis altitudes and maneuver magnitudes.

The altitudes utilized to achieve this heat rate profile are shown in Fig. 5. The minimum altitude employed was approximately 95 km compared to a minimum altitude of about 100 km for MGS. The large-scale shape of the altitude curve reflects the strategy of dipping down into the atmosphere early in the main phase to achieve the maximum heat allowable and then increasing the altitude as the heat limits declined. Heat rate limits declined during the endgame phase (Fig. 4) because integrated heating eventually dominates the peak heating that drove limits for the earlier aerobraking phases. Heat rate declines even more sharply during the final walkout phase to maintain a mean orbit lifetime of one day.

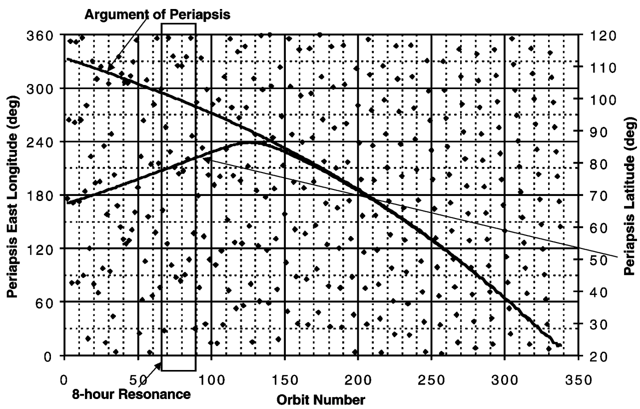

Fig. 6 Periapsis latitude and longitude.

The smaller-scale, sawtooth trend, evident especially in the second-half of aerobraking, is due to the natural drift in altitude due to oblateness effects. The oblateness of Mars causes argument of periapsis to precess causing a drift in periapsis location from an initial high northern latitude (~68°) toward the north pole and eventually back down to near equatorial latitudes (Fig. 6). ABMs are, therefore, required to correct these oblateness-induced altitude changes to maintain an acceptable average heat rate, even if the heat rate limits are fairly constant.

As the periapsis approaches the north pole (main phase 1), the periapsis altitude naturally increases, and thus, heat rate decreases in the absence of any maneuvers. The altitude drift rate is less pronounced in early main phase 1 due to solar gravity perturbations acting on the large-period orbits. After crossing the pole (main phase 2), the altitude naturally decreases.

The change in the direction of the natural periapsis altitude drift distinguished main phase 1 from main phase 2. Main phase was subdivided primarily due to differing fault response strategies. A problem delaying maneuver execution in main phase 1 could be tolerated with no danger to the spacecraft, whereas a time-critical response would have been required during main phase 2.

The magnitudes of the maneuvers performed to adjust the altitudes are also included in Fig. 5. In main phase 1, maneuvers smaller than 0.3 m/s were most frequently required, whereas larger maneuvers, up to 1.2 m/s, were used in the smaller period orbits of main phase 2 and walkout. To counteract the altitude drift due to oblateness, maneuvers to lower periapsis were most often required in main phase 1, and maneuvers to raise periapsis were needed in main phase 2 and walkout. One maneuver to raise periapsis was performed in main phase 1 (orbit 26), in response to concerns regarding a density wave peak predicted by AAG analysis. A second maneuver to raise periapsis was needed (orbit 74) to counteract a systematic altitude reduction caused by resonance with the Mars gravity field at an orbit period of ~8 h.

Aerobraking periapsis latitude started at about 68°, reached a maximum of 86°, and ended near 23° (Fig. 6). In early aerobraking, sparse longitudinal coverage prevented the development of detailed density wave models; therefore, increased caution, expressed in terms of a higher heat rate margin, characterized this initial period. In the later smaller period orbits, longitudinal coverage was much more extensive, which contributed to the decision to reduce heat rate margin when reduced density variability was observed near the north pole.

Mass concentrations in the Martian gravity field (such as Olympus Mons) result in orbital perturbations that can significantly affect the long-term trajectory, especially in cases where the orbit passes over those regions repeatedly in a short time. A nearly 2 to 1 resonance with the Mars rotation period (~12-h orbit period, in Fig. 6 near orbit 40) increased the inclination of the orbit by nearly 0.2° as shown in Fig. 7. Pre-MOI Monte Carlo analysis predicted that the inclination could change up to ±0.25 deg during the ~12-h resonance depending on the particular path taken through this region. Because this effect could not be uniquely predicted and factored into the MOI target, sufficient propellant was budgeted to correct the worst-case perturbation predicted by the aerobraking Monte Carlo results.

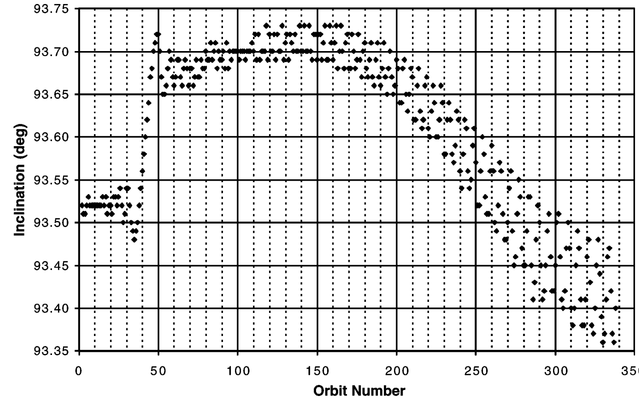

Fig. 7 Inclination (Mars mean equator date).

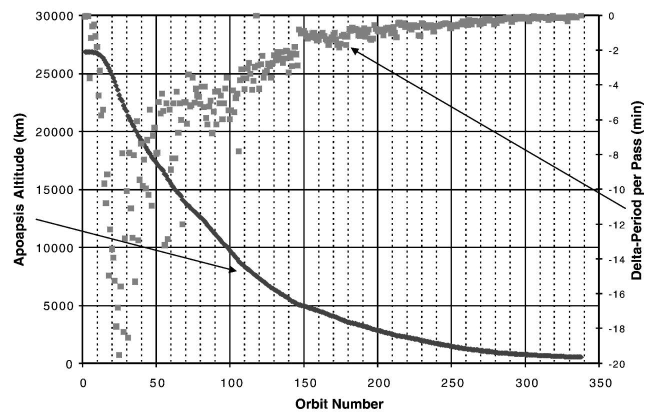

Fig. 8 Apoapsis altitude and delta period.

The nearly 3 to 1 resonance with the Mars rotation period (~8 h orbit period, highlighted in Fig. 6 near orbits 70–90) caused the spacecraft to encounter three distinct longitude ranges repeatedly. The effect of higher-order gravity harmonics near 210° longitude caused the altitude to decrease over 1 km with each periapsis passage in this region, opposing the natural altitude drift and necessitating a maneuver to raise periapsis during this resonance.

Monte Carlo analysis during the 12-h, and other less dominant resonances, was extremely helpful in recognizing the potential altitude variations due to the higher-order harmonics in the gravity field. Odyssey experienced nearly the maximum altitude and inclination change predicted by the Monte Carlo analysis. Correcting the inclination shortly after the ~12 h resonance period was considered (to take advantage of performing the maneuver in the larger orbit); however, correcting the inclination simultaneously with other large maneuvers that were required to transition to the mapping orbit following the end of aerobraking was more efficient (and operationally preferable).

The gradual decrease in inclination after about orbit 150 (Fig. 7) was predicted by all pre-MOI analysis and was accommodated by a +0.25 deg bias in the MOI inclination target.

Period reduction per drag pass is shown in Fig. 8. Early in aerobraking, the period could be reduced by 15–20 min with a single pass. In the smaller period orbits, the period reduction declined to only a few minutes for the same peak density and finally only a few seconds per pass at the greatly reduced densities during walkout. Figure 8 also includes the apoapsis altitude decay history starting from an initial altitude of about 27,000 km to 503 km at aerobrake termination.

Operations

Walkin

Contact with the Martian atmosphere was initiated four revolutions after Mars orbit insertion after the first ABM, which reduced periapsis altitude from 292 to 158 km. During the 10-day walkin phase, a total of 7 ABMs, performed every other orbit, gradually lowered periapsis altitude until heat rates within the main phase 1 heat rate corridor were achieved (Fig. 4).

The first two ABMs were designed to achieve a final density of 2 kg/km^3, which was deemed to be the lowest density that could be sensed by both the accelerometers and the orbit determination process. This initial density target was only 5% of the value corresponding to the middle of the heat rate corridor, to provide margin against the large initial uncertainty in the as yet uncalibrated atmosphere model. This density target was converted to an altitude target of 136 km using the MG2K atmosphere model.

An intermediate altitude target of 158 km, at which little to no atmospheric drag was anticipated, was selected to prevent overshooting the 136-km target altitude due to maneuver execution errors. Before walkin start, only one such intermediate orbit was planned, but during the first aerobraking pass, the spacecraft entered safe mode due to an inappropriate setting of a sequence parameter. The project quickly recovered, resulting in a delay of only one additional revolution at this altitude.

These first two altitude steps reflected a cautious strategy, because no empirical data were yet available to calibrate the atmosphere model. MGS provided a wealth of atmospheric data, but not at Odyssey's northern aerobraking latitudes nor during the Odyssey aerobraking season of northern hemisphere winter. Data from onboard accelerometers[10] and the total change in orbit period determined from the navigation orbit determination process[6] provided independent measurements of the atmospheric density that were used to calibrate atmosphere models during aerobraking.

ABMs to reduce altitude were performed every other apoapsis to sample the atmosphere at two different longitudes and to permit sufficient time for operational activities. Altitude steps resulting from ABMs 3–7 were determined by using an algorithm designed to balance the desire to achieve heat rates within the design corridor as quickly as possible with the need for conservatism due to the lack of empirical data to calibrate atmospheric and spacecraft thermal models.

Using this algorithm, the selected altitude step was the lesser of either 1) the accelerometer derived scale height or 2) the altitude step that would result in a heat rate corresponding to the middle of the heat rate corridor (0.23 W/cm^2) assuming the scale height was a conservatively small 4 km and using a simple exponential atmosphere model. Method 1 governed the design of ABMs 3 and 4, and method 2 governed the design of ABMs 6 and 7. Both methods yielded the same altitude step for ABM 5.

Main Phase and Endgame

In main phase, the maximum allowable heat rate is constrained by the peak solar array heating on each pass. The solar array provides the majority of the drag area and is the spacecraft's most thermally sensitive component. Most of the period reduction occurs in main phase because this phase contains the maximum heat rates and the larger orbit periods increase the period reduction achieved for a given level of drag. In endgame, cumulative heating limits maximum heat rate due to the longer drag pass durations. For Odyssey, a maximum heat rate limit was established that reflected the cumulative heating constraint. Thus, the only difference in heat rate constraints between main phase and endgame was a slightly different thermal limit.

The navigation strategies, as detailed later, were significantly different between main phases 1 and 2, but from a spacecraft perspective, the biggest difference between these phases was the enabling of an autonomous popup capability. Recall that in phase 2 if no maneuvers were performed, the vehicle would naturally drift to increasingly lower altitudes, eventually exceeding the thermal limits. To reduce the risk of catastrophic failure in such an event, commands were enabled onboard the spacecraft at the beginning of phase 2 to execute autonomously a maneuver to raise the periapsis altitude out of the atmosphere if the spacecraft entered safe-mode. Popups were undesirable because they consumed considerable propellant, not only to raise the spacecraft out of the atmosphere but then to reestablish aerobraking. The total ΔV that would have been expended had a popup occurred ranged from 6 to 26 m/s and increased as orbit period decreased. No popups occurred during Odyssey aerobraking.

Margin Maintenance Strategy

The most operationally intensive trajectory analysis task during aerobraking was providing information used to manage the aerobraking margins. This involves trading thermal and lifetime limits (which generally require higher altitudes to increase margin) with aerobrake duration and number of drag passes (which require lower altitudes for minimization). The primary means by which these margins are managed is through the maneuver strategy that raises or lowers the periapsis altitude to adjust the drag achieved on each pass. Given the changing atmospheric conditions, the phase-dependent constraints, and the risk management tradeoffs associated with each decision, the maneuver strategy was continually monitored and adjusted throughout aerobraking to reflect the current conditions.

The guiding philosophy of the maneuver strategy was to reduce period as quickly as possible while maintaining acceptable margins and maneuver frequencies. Guidelines and criteria for heat rate targeting and maneuver selection were developed before the start of aerobraking. This established a structure for the operational discussions and recommendations, but the daily ABM decisions were dependent on the recent experience, the day-to-day atmospheric variability, and the evolving risk tolerance. Early in aerobraking, a more cautious approach was taken in response to an unexpectedly high level of variability. Near the north pole, less heat rate margin was accepted due to a reduction in observed density variability and the fact that aerobraking had fallen behind the baseline plan. By the end of main phase 2, aerobraking progress had caught up to, or even exceeded, the original plan, permitting greater conservatism in heat rate margin at little additional risk to successful completion of aerobraking.

The two most influential constraints on the maneuver selection were intended to reduce the workload associated with implementing the ABMs. Only one ABM was permitted per day, and ABMs were permitted only on specified orbits to not corrupt onboard sequence timing. Given these constraints, each ABM was required to adjust the predicted densities on all orbits that would occur between ABM opportunities ($\sim$24 h) such that the densities remained within the specified corridor.

Evaluating the Thermal Margin

Each day, one or more of the following data were used to evaluate the thermal margin in support of maneuver recommendations.

First, starting with initial conditions provided by orbit determination of the most recent drag pass, the trajectory was propagated using a variety of atmospheric models. Although several wave models (models that attempted to fit the observations to selected sine and cosine functions) were often evaluated each day, maneuver recommendations were most often based on the model that included only the constant multiplier to the MG2K model with no longitude dependence.

Next, Monte Carlo analysis was performed to evaluate the effect of atmospheric uncertainty on the predictions. In its first use for an aerobraking mission, atmospheric Monte Carlo analysis provided valuable insight into the atmospheric variability.[7] The standard deviation of the total MG2K multiplier (Fig. 2) was a critical input to the Monte Carlo process because it dominated the variability that was modeled. Following the unexpectedly high heat rate of the periapsis 106 pass, the project established a lower bound of 20% 1-σ on this multiplier, regardless of the formal statistics, to protect against statistical anomalies. This constraint was maintained throughout most of the remainder of aerobraking.

A four-point running mean of heat rate was also computed (Fig. 4) to aid in corridor control maneuver decisions and was particularly useful any time extreme variations in individual passes were present and the danger of an individual pass violating the flight allowable limit was perceived to be negligible. Past densities were sometimes extrapolated to the altitudes expected for future passes, using an exponential model and an assumed scale height as a method to generate a model independent of MG2K. This method was typically used after a high heat rate pass occurred that was not well predicted by either navigation or accelerometer predicts.

Finally, deterministic solar array temperatures predicted by the LaRC thermal team[9] were computed each day to support maneuver recommendations; however, these thermal predictions were dependent on heat rate predictions and, thus, were not a completely independent data source. The data also served as an independent validation of the temperature reconstructions supplied by the prime thermal subsystem team at Lockeed Martin.

Maneuver Decision Criteria

After a prediction of heat rates for the next daily maneuver interval lasting ~24 h was generated, the next step was to determine whether an ABM was required to maintain appropriate thermal or lifetime margin (increasing periapsis altitude), or whether an ABM to increase the heat rate was appropriate (reducing periapsis altitude).

The navigation team primarily utilized strategies involving deterministic propagations for maneuver recommendations, but Monte Carlo results supplied by LaRC[7] were weighted heavily by both the navigation team and the project management in maneuver decisions even though Monte Carlo analysis was not in the critical path for operations.

In general, ABMs were used to constrain the nominal heat rate within the specified corridor and to produce Monte Carlo 99% values that were below the flight allowable limits. Although the flight allowable limit was the strictest thermal constraint, an immediate action limit was also specified to act as a trigger against the possibility of a future excursion above the flight allowable limit. If any heat rate, as determined by the thermal subsystems reconstruction, was higher than the immediate action limit, the operations plan called for a maneuver to be executed at the next available opportunity to raise the periapsis altitude (to effectively lower the future predicted heat rates). Although no formal constraint restricted targeting relative to the immediate action limit, early in aerobraking the project frequently selected maneuvers to restrict the 99% high Monte Carlo heat rate predictions to values below this immediate action limit in an attempt to provide even more conservatism in the presence of the high variability that was observed during that time period.

In main phase 1, maneuvers to lower periapsis were generally recommended if the predicted densities in the interval under consideration were predominantly in the lower-half of the corridor; however, concerns regarding the high level of variability often dominated the desire to proceed more aggressively forcing the project to target lower in the corridor than anticipated in the pre-MOI plans.

In main phase 2, a maneuver was generally performed if any pass during the daily maneuver interval was predicted to exceed the upper corridor limit (which maintained 70–100% margin with respect to the flight allowable limit), or if the 99% Monte Carlo heat rate of any pass exceeded the solar array flight allowable temperature. Because ABMs could only be performed on specific orbits, it was often necessary to perform the maneuver several (up to four or five) orbits before the pass that was actually of concern. This lowered the heat rate on the earlier passes and reduced the average drag more than would have resulted if the ABM could have been delayed.

Maneuver Selection

Once it was determined that a maneuver was required, the strategy for selecting the appropriate maneuver size was a tradeoff between aerobraking as quickly as possible, maintaining large heating rate margins to reduce the thermal risk, and maintaining a reasonable maneuver frequency. During most of main phase 1, maneuvers that increased the density to near the top of a 100% margin corridor were recommended because heat rate naturally decreased during this phase. This strategy resulted in the most rapid aerobraking possible while providing margin consistent with the variability that was observed. Given the high level of variability, two or more small steps were often preferred to a single larger altitude reduction, even though this increased the maneuver frequency.

In main phase 2, because the heat rate naturally increased, ABMs were designed to reinitialize the heat rate to the bottom of the corridor to allow time for the upward heat rate drift before the next ABM was required. To maintain the highest average heat rate possible, the smallest maneuver that would keep the heat rate within the constraints for approximately 1–2 days was often selected. The MG2K model tended to underpredict density during this phase (as reflected in Fig. 2 by the decreasing average total scale factor applied to the MG2K model), causing the predicted heat rate to often exceed the observations. The declining density often caused the project to delay the epochs of maneuvers that were anticipated to be required based on preliminary analysis. Smaller maneuvers were occasionally selected in anticipation of the diminishing atmosphere with the knowledge that a maneuver could be performed earlier than might be expected (still meeting the one per day constraint) if the atmospheric density increased for any reason.

Additional ABM Decision Factors

Several additional factors were considered in the formation of ABM recommendations. First, the predicted final LTST was continually compared against the 1400 hrs (earliest acceptable LTST) constraint as a measure of the aerobraking progress. Because it is difficult to predict the final LTST based on current conditions, the actual LTST vs period curve (Fig. 9) was compared to that of a reference aerobraking profile (also included in Fig. 9) that satisfied the final LTST constraint. The reference curve reflects a deterministic trajectory, developed post-MOI assuming a nominal atmosphere and an ABM strategy that satisfied all constraints. Although it was recognized that this reference trajectory represented only a single example of a successful aerobraking profile, measuring progress against this reference provided a straightforward means of evaluating the current LTST margin.

The LTST vs period curve proved to be a better metric for Odyssey than the period vs time curve utilized by MGS because it reflected the two parameters that were explicitly constrained, LTST and final period.

Throughout main phase 1, at a given value of period, the actual LTST was earlier than the reference profile. At this time, aerobraking was behind the reference profile due to the additional conservatism that was applied in most of main phase 1. To make up for this deficit, more aggressive strategies were applied whenever reasonable to reduce this differential and increase the margin in the predicted final conditions relative to the 1400 hrs constraint. This was one consideration in the reduction of the upper heat rate corridor margin to values below 100% near the pole where decreased atmospheric variability was observed.

When the LTST deficit with respect to the reference profile was erased (at a period of ~5.5 h shown in Fig. 9), a more conservative heat rate margin strategy (100% margin) was acceptable because long-term runouts and Monte Carlo's predicted significant margin relative to the 1400 hrs LTST constraint. However, the desire to reduce the number of passes still encouraged targeting high in the heat rate corridor whenever possible.

On a weekly basis, aerobraking Monte Carlo runs through the end of walkout were performed by LaRC, yielding statistics such as

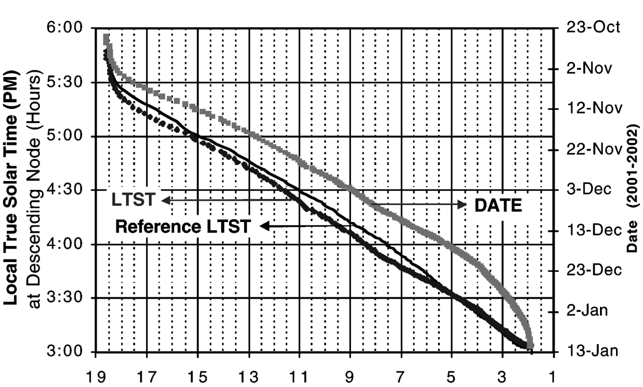

Fig. 9 LTST and date.

the number of days and revolutions remaining, expected number of maneuvers and ΔV required, and final state of the spacecraft including LTST.[7] If the 99% early final LTST was earlier than 1418 hrs [1400 hrs power constraint plus 18 min (nine day) dust-storm and safe-mode margin], a more aggressive aerobraking strategy characterized by higher heat rates was recommended. A sample deterministic trajectory for the same time period was generated several times using the operational software set to validate the LaRC Monte Carlo results.

A final consideration in maneuver selection was the number of drag passes associated with each maneuver possibility. Because each aerobraking pass involves some degree of risk, maneuver recommendations that minimized the number of drag passes were preferred. To distinguish between two similar, but not identical, maneuver choices, the difference in the number of drag passes to achieve a common orbital period was estimated utilizing the difference in predicted orbit period at the same epoch a day or more downstream from the maneuvers and the predicted period reduction per pass. The maneuver strategy resulting in the fewest drag passes was usually selected.

Walkout

When the apoapsis altitude had decreased to the point where the continuing apoapsis decay would result in impacting the planet within one day if not prevented, the primary constraint changed from heat rate to maintaining an acceptable orbital lifetime. This marked the transition from main phase/endgame to walkout.

For Odyssey, the orbit lifetime was defined as the time between any given apoapsis and the first apoapsis for which the altitude is predicted to be less than 300-km altitude. (This is consistent with the MGS definition.[2]) Odyssey was required to maintain a mean lifetime of greater than or equal to 24 h. The project also required a 99% low lifetime of greater than 8 h to accommodate a worst-case Deep Space Network single station outage that prevented spacecraft commanding. LaRC Monte Carlo analysis indicated that the 99% limit was automatically satisfied by the mean requirement because a 24-h mean lifetime yields approximately a 15–18 h 99% low lifetime.

Pre-MOI analysis determined that the transition to walkout would occur at an apoapsis altitude of ~1500 km. LaRC Monte Carlo analysis produced an approximate heat rate limit that represented the lifetime requirement for preliminary design work (Fig. 4) but during operations, lifetime was calculated explicitly on a daily basis with both nominal propagations and Monte Carlo runs to determine the appropriate maneuver strategy. An average of one ABM per day was executed in this phase to meet the requirement.

Aerobraking Termination

On 11 January 2002, aerobraking was terminated by a propulsive maneuver that raised periapsis altitude out of the atmosphere to an altitude of 201 km and left the spacecraft in an intermediate transition orbit. At termination, the LTST was 1504 hrs and apoapsis altitude had decayed to 503 km.

Four additional propulsive maneuvers were used to further raise periapsis altitude, perform a minor adjustment to inclination (in conjunction with the second periapsis raise maneuver to save fuel), and further reduce apoapsis altitude to achieve the desired science orbit. All maneuvers were successfully executed, permitting the science mapping phase of the mission to commence as planned on 19 February 2002.

The mean periapsis and apoapsis altitudes of the resulting science orbit are ~387 and ~451 km, respectively, and the orbit period is ~1.9 h. A slow drift to later LMST is required to satisfy certain science observations and is achieved through the use of a slightly non-sun-synchronous average inclination of 93.14 deg (Mars mean equator of date).[6]

Strategic Propellant Utilization

Propellant in excess of the amount needed to satisfy the two Mars year primary mission objectives to 99% confidence is referred to as strategic propellant. This fuel was allocated by using an algorithm that carefully balanced the need to maintain adequate contingency reserves to ensure prime mission completion with the possibility of extending mission duration.

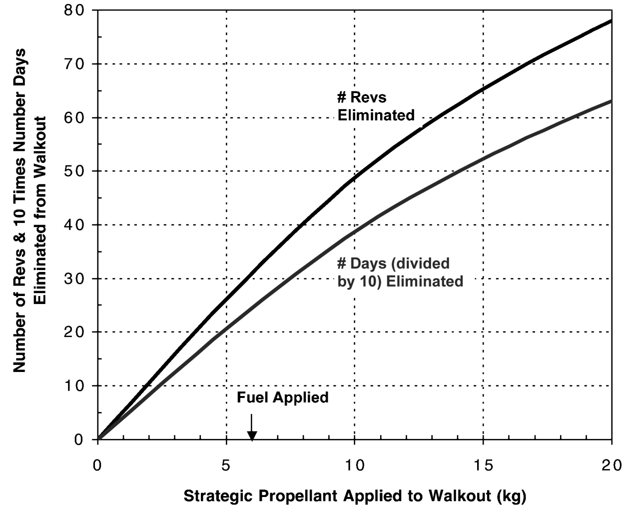

Fig. 10 Impact of strategic propellant.

Walkout was considered by the Odyssey project to be the riskiest phase of the mission and was, therefore, earmarked for reduction through the use of strategic fuel. Just before the end of aerobraking, a ΔV Monte Carlo analysis predicted 13–19 kg of total strategic fuel available. Strategic propellant totaling 6 kg (equivalent to a ΔV of ~30 m/s) was used to terminate walkout earlier than an aerobraking design whose sole goal was to minimize fuel consumption. Early walkout termination eliminated ~2.5 days and ~30 revolutions from the walkout phase (Fig. 10). Walkout was terminated at an apoapsis altitude of 503 km.

Conclusions

The Mars atmosphere proved to be more unpredictable and variable for Odyssey than for MGS. Unlike MGS, no longitude-dependent density wave models were found to provide reliable improvement in predictive capability. The additional atmospheric data gained during Odyssey aerobraking, however, should be invaluable to the improvement of future Mars atmospheric models.

Odyssey aerobraking was completed successfully and slightly ahead of plan due in large part to the preparation and dedication of all involved. Like MGS, Odyssey aerobraking was a high intensity activity requiring continual monitoring and assessment of various risk elements. The experience gained during MGS aerobraking proved of invaluable assistance to Odyssey. The Odyssey aerobraking experience now adds to this legacy.

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