MAVEN Transition-to-Science Maneuvers and Comet Siding Spring

Brian Young* and Stuart Demcak† and Paul Stumpf*and Min-Kun Chung*

Jet Propulsion Laboratory, California Institute of Technology,

4800 Oak Grove Drive, Pasadena, California 91109

David Folta‡

NASA Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, Maryland 20771.

After the September 2014 arrival of the Mars Atmosphere Volatile Evolution mission (MAVEN) at Mars, the spacecraft was to perform five maneuvers to reduce the orbit period from 35 to 4.5 hours, and lower the periapsis altitude into the target in-situ science density corridor. While in route, however, the potential threat — and science opportunity — from Comet C/2013 Siding Spring crystallized, and the plan had to be modified to shield the spacecraft behind Mars and support new observations. This paper describes the plan modifications, Monte Carlo analyses necessary to ensure success, and results of executing the modified plan.

I. Introduction

The Mars Atmosphere Volatile Evolution mission (MAVEN) is a mission funded by NASA's Mars Scout Program. Managed by NASA's Goddard Space Flight Center, the mission is dedicated to studying the upper atmosphere of Mars, and its loss due to the solar winds.[1] The spacecraft is designed to fly through the upper atmosphere, targeted to a 0.05–0.15 kg/km^3 periapsis density "corridor", to perform in-situ and remote studies from a 4.5 hour elliptical orbit.

MAVEN launched on Nov. 18, 2013 for a 10 month cruise to Mars, inserting into a 35 hour orbit on Sep. 22, 2014. At launch, the plan was to transition into the science operations mode by reducing the orbit period and altitude through a sequence of three periapsis lowering maneuvers (PLMs) and two period reduction maneuvers (PRMs).[2] The comet C/2013 Siding Spring (CSS), discovered before launch in early 2013, was found to be on a trajectory that would fly by Mars on Oct. 19, 2014, when the existing transition plan specified that MAVEN would be stepping into the final density corridor.[3] Because the trajectory of the comet and its debris field were poorly known until early 2014, formal planning had to be delayed until after launch.

With early 2014 Earth-based observations, it was determined that while the 135,000 km fly-by would not pose an extreme risk to the spacecraft, the most prudent action would be to shield the vehicle behind the bulk of Mars at the time of maximum particle flux, while shutting down most spacecraft systems to minimize risks from particle impact.[4] In addition to the direct risk of particle impact, the interactions of the particle field with the atmosphere led to both additional concerns and opportunities. The comet particle field was likely to significantly increase the density of the atmosphere at the targeted altitudes, requiring additional care when targeting to the density corridor. At the same time, the instruments on-board the vehicle were uniquely suited to studying these interactions, providing a valuable and unexpected opportunity to collect science observations of an otherwise difficult to observe process.

Thus, the team was required to re-formulate the five-year-old transition-to-science plan to achieve the mitigation strategy, accommodate new observations, and still achieve the desired science orbit without a

*MAVEN Maneuver Analyst, Mission Design and Navigation Section

†MAVEN Navigation Lead, Mission Design and Navigation Section

‡MAVEN Mission Design Lead, Navigation and Mission Design Branch

significant delay to the start of science operations. Due to the late time line, this had to be done over a few months while also performing cruise operations tasks, leaving enough time before the approach and orbit insertion to allow the project, the Mars Program Office and management to critique and revise the plan. This paper describes the original plan, how it was modified, Monte Carlo studies implemented to ensure success, and the results of the implementation.

II. Maneuver Planning

II.A. Baseline plan

Following the Mars Orbit Insertion (MOI) maneuver that placed the vehicle into a 35 hour, 380 km periapsis altitude orbit, the transition-to-science plan was designed to reduce the period of the orbit to the maximum allowed 4.61 hours, lower the periapsis altitude into the target density corridor of 0.05–0.15 kg/km^3, and allow time for the deployment and engineering checkouts of instruments. The schedule of maneuvers to achieve this is shown in Table 1.

Table 1. Original Transition Maneuver Plan

Name	**Epoch**	**Δv (m/s)**	Target	Details
PLM-1	MOI+1.5 orbits, Sept. 24, 2014	6–10	Peri. Alt.: ∼200 km	Menu-driven at apoapsis to reduce altitude
PRM-1	MOI+3 orbits, Sept. 26, 2014	455	Period: ∼5.5 hours	Pre-defined periapsis pitch-over on main engines for large period reduction
PRM-2	MOI+10 days, Oct. 2, 2014	70–100	Period: 4.63 hours	Targeted at periapsis to final desired orbit period
PLM-2	MOI+14 days Oct. 6, 2014	2–6	Density: ∼0.05 kg/km^3	Menu-selected at apoapsis to begin walk-in to near top of density corridor
PLM-3	MOI+22 days, Oct. 14, 2014	1–5	Density ∼0.15 kg/km^3	Menu-selected at apoapsis to get deeper into the density corridor
OTM-0	MOI+38 days, Oct. 30, 2014	0–3	Density: 0.05–0.15 kg/km^3	Menu-selected at apoapsis to return to density corridor and start science phase

The first three maneuvers were to be executed as rapidly as possible after MOI to get into the approximate final orbit. PLM-1 reduced the altitude from a post-MOI range of 370–400 km down to around 200 km, improving the efficiency of the period reduction maneuvers (PRMs) while staying far enough above the known extents of the atmosphere to maintain safety. Because a significant amount of energy needed to be removed from the orbit, the first period reduction maneuver, PRM-1, was implemented as a blunt tool to burn in the anti-velocity direction and greatly reduce the size of the orbit. As PRM-2 would be necessary to fine tune the results and correct any execution errors, it was determined that PRM-1 could be a single pre-designed maneuver with only a timing update required after MOI to re-center it on periapsis, allowing rapid implementation in the early days of the transition. PRM-2 would then be targeted precisely to the final desired period using a full design sequence.

The next three maneuvers, PLM-2, PLM-3, and OTM-0 were to be implemented from a menu of pre-built apoapsis burns that would also be used for weekly Orbit Trim Maneuvers (OTMs) during primary science phase operations to re-target the density. These spread from -6.0 m/sec to +6.0 m/sec (in the velocity direction), with a spacing of 0.3 m/sec. In general these were to be targeted by estimating a multiplicative scale factor to be applied to a reference MarsGRAM2005[5] model of the atmosphere for reconstructed orbits, and then using that factor to predict future behavior.[2]

The long duration between PLM-2 and the start of science operations at OTM-0 was planned to allow for instrument deployments and checkouts that needed to be performed while the spacecraft was near its

operational regime in the atmosphere. Additionally, the time between these three maneuvers was seen to be useful for trending the behavior of the atmosphere, getting long-term averages of the scale factor to better aid targeting of the subsequent maneuvers.

II.B. Comet Siding Spring plan adjustments

Following Earth-based observations, the closest approach of Comet Siding Spring to Mars was determined to be on Oct. 19, 2014, after the planned PLM-3 maneuver. The risks from the comet were two-fold: first, the particles forming the coma of the comet could impact the vehicle at velocities exceeding 60 km/sec, and second, these particles might cause the atmospheric density to "bloom" rapidly, leading the spacecraft to encounter densities for which it was unprepared. Mars Program Office guidance for all Mars orbiters was to shield the spacecraft behind Mars at the epoch of maximum particle fluence, 20:07 UTC, mitigating the direct impact risk. The atmospheric blooming risk, which was unique for MAVEN, was to be mitigated by targeting a density well shallower than that deemed safe for the spacecraft configuration. Finally, feedback from project scientists indicated that two days of observations before and after the encounter, for a total of four days of science observations, were desirable to understand the behavior of the coma/atmosphere interactions and take advantage of this fortuitous opportunity to observe an event that would be impossible to observe in other circumstances.

In order to collect in-situ science measurements around the comet encounter, and to proceed into the nominal science phase as quickly as possible after the encounter, the project decided that it was safe to be near the shallow end of the density corridor for the comet encounter, since a tripling of density would still be within the nominal corridor, and the spacecraft would be configured for safety with unecessary systems already shut down due to the direct particle impact risk. However, PLM-3 would then need to be delayed from Oct. 13 to Oct. 23, 2014, four days after the encounter, since going deeper than the low-density end of the corridor before the encounter would be detrimental. The need for additional equipment validation after the encounter, to confirm that no damage occurred, required the start of science operations (OTM-0) to be delayed until two weeks after PLM-3, requiring an additional PLM-4 to be inserted a week after PLM-3.

To usefully shield the spacecraft behind Mars, the objective was to center the 28 minute occultation with respect to the direction of the particle flux around the epoch of maximum particle fluence, as shown in Figure 1. Based on the known orbit orientation, this could be approximated as targeting a 30° mean anomaly at the maximum particle fluence epoch, requiring a modification of the PRM sequence. A tolerance of approximately 2 minutes or 2.6° was specified by the project as being acceptable, since the length of the occultation was sufficiently long. PRM-1 was left in place, as a fixed ΔV occurring three orbits after MOI, since PRM-2 was already intended to be the precision component. Instead of targeting a period, PRM-2 would need to be targeted to achieve the desired phasing, accumulating period changes over sixteen days. Due to uncertainty in the initial orbital period before PRM-2, the final period could only be roughly selected with a 0.06 hour precision, with the jump representing a change from an (e.g.) 84 revolution transfer to an 85 revolution transfer. Further complicating this was that PLM-2 was planned to occur between PRM-2 and the encounter, which would both directly cause an orbit period change, and also move the spacecraft into the atmosphere where drag would begin to accumulate and further disrupt the phasing of the orbit. Thus, the design of PRM-2 needed to target the phasing (accounting for the possibility of "wrapping" to a different number of orbits) while including a PLM-2 selection and the post-PLM drag.

Because PRM-2 was still large, 70–100 m/sec, and the drag after PLM-2 may have been significantly different than planned, it was determined that PRM-2 itself was not capable of achieving the two-minute precision desired by the project. For this reason, a PRM-3 was inserted into the sequence on Oct. 13, 2014 to correct PRM-2 execution errors, and account for an improved understanding of the drag regime after collecting scale factor values over the intervening days. This was expected to be a less than 3 m/sec and be all along-track, with a designed ΔV in either the velocity or anti-velocity direction. A table of the new plan, comparable to the original, is shown in Table 2. This plan was finalized in May 2014, only a few months before implementation.

III. Monte Carlo Studies

The desired goals, especially the phasing of the orbit to put the spacecraft at a particular mean anomaly at a specific time, required a level of precision not originally considered for the mission. Thus it was important

Table 2. Modified Transition Maneuver Plan

Name	**Epoch**	**Δv (m/sec)**	Target	Details	Changes
PLM-1	MOI+1.5 orbits, Sept. 24, 2014	6–10	Peri. Alt.: ∼200 km	Menu-driven at apoapsis to reduce altitude	No change
PRM-1	MOI+3 orbits, Sept. 26, 2014	455	Period: 5.5 hours	Pre-defined periapsis pitch-over on main engines for large period reduction	No change
PRM-2	MOI+10 day, Oct. 2, 2014	70–100	CSS Phasing with period ∼4.63 hours	Periapsis pitch-over targeted to CSS phasing near desired period	Switched to phasing target from period target
PLM-2	MOI+14 days, Oct. 6, 2014	2–6	Density: ∼0.05 kg/km^3	Menu-selected at apoapsis to begin walk-in near top of corridor	Now selected as part of PRM-2 design
PRM-3	MOI+17 days, Oct. 9, 2014	0–3	Final CSS phasing	Δv in the velocity or anti-velocity direction	Added to sequence to achieve precise phasing target
PLM-3	MOI+31 days, Oct. 23, 2014	1–3	Density: ∼0.15 kg/km^3	Menu-selected at apoapsis to get deeper into the density corridor	Delayed until after CSS encounter
PLM-4	MOI+37 days, Oct. 29, 2014	0–3	Density: in corridor	Menu-selected at apoapsis to maintain density corridor	Added due to delayed start of science
OTM-0	MOI+48 days, Nov. 9, 2014	0–3	Density: in corridor	Menu-selected at apoapsis to return to density corridor and start science	Delayed due to CSS encounter

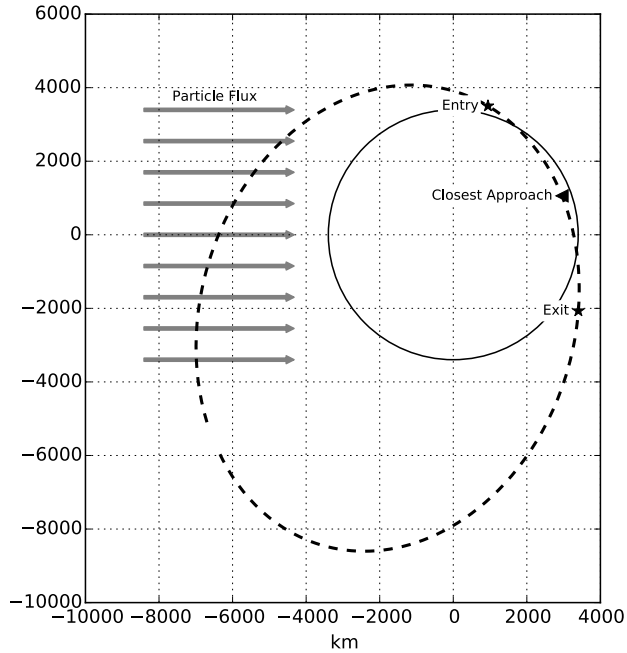

Figure 1. Geometry of particle flux occultation target for Comet Siding Spring encounter shielding

to understand the statistical effects of the random variations in the trajectory to determine if the selected plan was sufficient to achieve the goals, and that it could be executed without costing significantly more fuel. In addition to the size of the maneuvers, fuel costs also had to consider the hidden costs associated with a lower initial period, which would need to be boosted earlier in the mission. There are multiple sources of uncertainty: the initial period and phase of the orbit after the sequence of MOI, PLM-1 and PRM-1, the execution errors in PRM-2, PLM-2 and PRM-3, and the accumulated atmospheric drag after PLM-2.

Because these results were in a closed elliptical trajectory with approximately 110 revolutions between MOI and the start of science operations, typical linearized Monte Carlo tools were inappropriate for the task. Instead three simulation methods based off of simple conic propagation were used to run Monte Carlo analyses. The first, a simple period accumulation model was used to understand the need for the PRM-3 phasing clean-up maneuver and to select its placement. The second simulation considered only the drag errors to understand the effects of the atmospheric uncertainty. Finally, a higher fidelity conic simulation model using maneuver selection criteria, execution errors, and stochastic drag effects was used to validate that the entire sequence was capable of meeting the desired goals.

III.A. Simple Accumulated Period Model

The first task was to understand if PRM-2 was capable of achieving the phasing goals, and then determine where a PRM-3 would need to be placed if it were deemed necessary. For this, the model needed to track the accumulated period and phasing across the orbits between PRM-2 and the CSS encounter, using the equations:

$$P_f = P_0 + \frac{\partial P}{\partial v}(\Delta v_2 + \Delta v_3) \tag{1}$$

$$\Delta t_f = \Delta t_0 - (P_T - P_0)n_2 + \frac{\partial P}{\partial v}(n_2 \Delta v_2 + n_3 \Delta v_3) \tag{2}$$

where Δv_2 and Δv_3 are the sizes of PRM-2 and PRM-3, the partial derivative $\partial P/\partial v$ for periapsis maneuvers is $\sim$31.5 sec/(m/sec) at the nominal orbit shape, P_0 and P_f are the initial and final orbit periods, n_2 and n_3 are the number of orbits between PRM-2 and PRM-3 and the encounter, P_T is the desired target period, and Δt_0 and Δt_f are the initial and corrected time from periapsis at the CSS max fluence epoch. Based on the schedule, n_2 was fixed at 90 orbits, while n_3 was allowed to vary anywhere between 10 and 80 orbits.

The initial period, taken from previous Monte Carlo results was known to have a mean of 5.45 hours with a 3σ variation of 0.135 hours, while the initial phasing (Δt_0) was assumed to be unknown and uniformly distributed between $\pm\frac{1}{2}P_T$. Note that the second term of phasing equation 2 is included to subtract out the accumulation of mean anomaly over multiple orbits, and is simply a modulo operation with a known modulus explicitly called out.

The spacecraft team delivers execution error models for maneuvers of various sizes. For the purposes of these studies, only the magnitude errors are important, and these were defined to be:

$$3\sigma_{\Delta v} = \begin{cases} 0.02\Delta v + 0.02 \text{ m/sec} & \Delta\text{v} < 10 \text{ m/sec} \\ 0.01\Delta v + 0.02 \text{ m/sec} & \Delta\text{v} \geq 10 \text{ m/sec} \end{cases} \tag{3}$$

With a nominal Δv_2 of -97 m/sec to achieve P_T, according to this simple model, the approximate 3σ errors for this burn were 1 m/sec, which accumulated through 90 orbits yield a 3σ error in the CSS phasing of 45 minutes. Thus it was determined that a third cleanup maneuver was necessary to meet the precision phasing goal.

Placement of the third PRM was a trade between fuel usage and precision; an earlier maneuver required less fuel for the same effect, but later maneuvers minimized the errors caused by the constant term in execution error equation 3. The earliest the maneuver could occur was approximately ten orbits or two days after PRM-2, to allow for reconstruction and planning. The latest it could occur was ten orbits before the encounter, to allow uninterrupted science observations. A Monte Carlo process was executed using these equations that first sampled the initial period and phase, selected a PRM-2 Δv, applied execution errors, and then selected a PRM-3 Δv based on the known executed PRM-2, before applying execution errors to that maneuver as well. Statistics on 10,000 samples for the total Δv, period, and phasing error were computed for multiple cases, considering the placement of PRM-3 parametrically. The results of this parametric study, shown in Figure 2, indicate that all of the available options were sufficient, though the range from 30–60 orbits demonstrated a good balance between precision, Δv and maintaining a reasonable minimum period. Computing the Δv for the original strategy as between 85 and 109 m/sec[1], using the same approximations, shows that the increase in fuel usage is less than 1.5 m/sec, or 3 m/sec once the hidden costs of period losses are included.

III.B. Drag-induced error studies

Because there was a desire to be near a 0.05 kg/km^3 periapsis density before the encounter, and drag can have a significant effect on the period and phasing (approximately 0.1 sec per pass at this altitude), it was important to understand the effects of that drag. Experience from previous aerobraking missions had shown that an effective way to understand the density variation was to estimate an engineering multiplicative "scale factor" that scaled a fixed MarsGRAM 2005 model. This scale factor demonstrates a relatively stable mean value that varied on the time scale of weeks between values of 1/3 and 3, with additional orbit-to-orbit variations of $\pm 105\%$ 3σ, following a log-normal distribution. Based on this understanding, a random sample of the atmosphere can be modeled such that the logarithm of the scale factor obeys the distribution

$$E[\beta_i \beta_j] = \sigma_0^2 \delta_{ij} + \sigma_m^2 \exp\left[-\frac{|\Delta t_{ij}|}{\tau}\right] \tag{4}$$

where the value $\sigma_0 \approx 0.24$ is the orbit-to-orbit variability, $\sigma_m \approx 0.36$ is the mean variability, and $\tau \approx 55$ days is the time constant of the mean variability. These values were computed from MRO and Odyssey data.[6] The factor Δt_{ij} is the time difference between any two periapses, and δ_{ij} is the Dirac delta.

Given the approximate period loss per pass at a given density, and knowing that the period change scales linearly with the drag Δv and the density level, the final period shift Δp and phasing shift Δt from the nominal for a sequence of sampled scale factors $\log \beta_i$ could be computed using the sums

[1] the actual nominal was lower, near 80 m/sec, due to non-conic perturbations

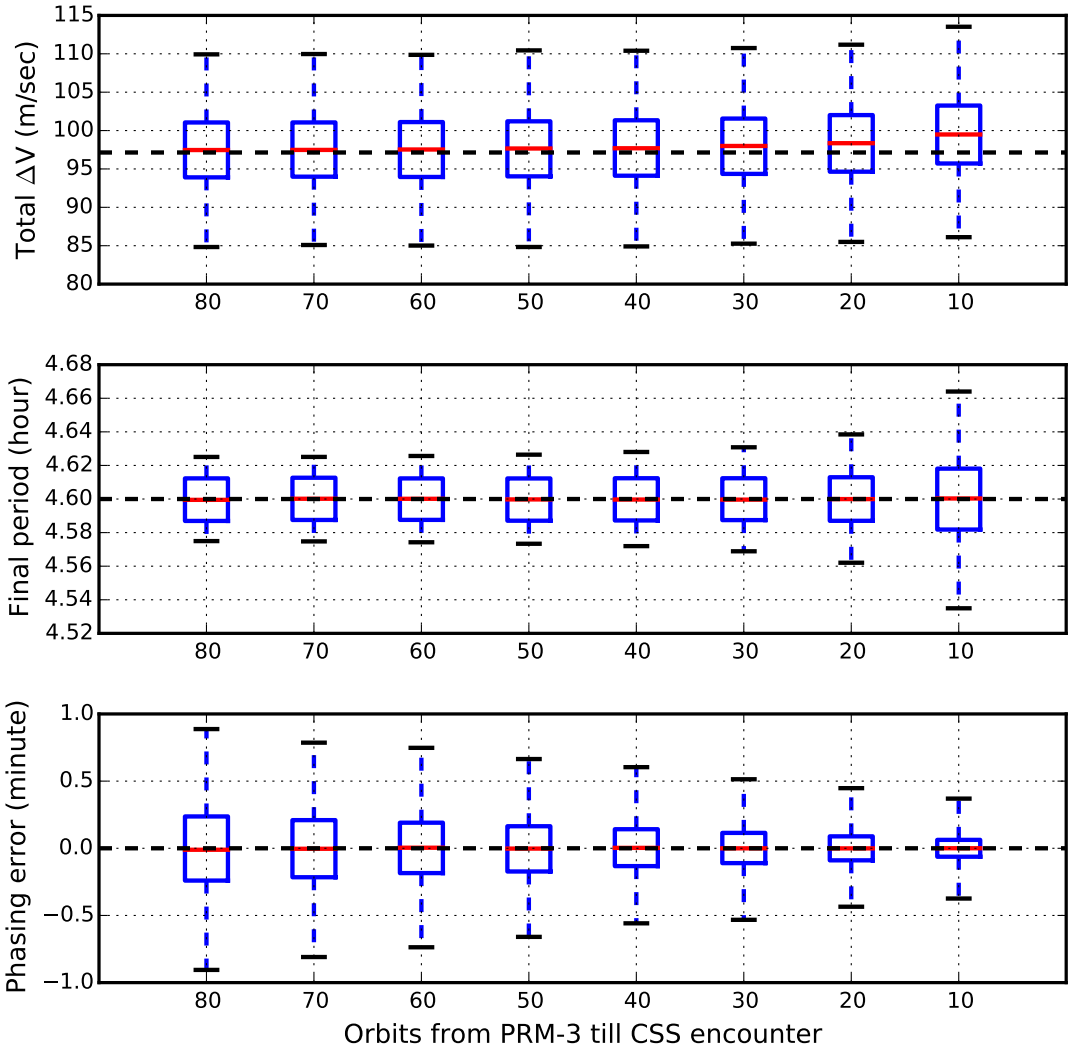

Figure 2. Statistics of parametric PRM-3 placement study with simple accumulated period model

$$\Delta P = \sum_{i=1}^{N} \frac{\partial P}{\partial \rho} \rho_0 \log \beta_i \tag{5}$$

$$\Delta t = \sum_{i=1}^{N} i \cdot \frac{\partial P}{\partial \rho} \rho_0 \log \beta_i \tag{6}$$

for a given target density ρ_0 and number of orbits N, where the partial derivative of period loss to density on average for the MAVEN shape, mass and orientation was -2 sec/(kg/km^3).

Before PLM-2, the mean scale factor would not be known, and could only be determined after being in the atmosphere for a few orbits. Because this mean component is applied every orbit, its effects on phasing accumulate quadratically with time if there is no chance for correction. To understand this effect, one million samples of scale factor sequences were sampled from the covariance specified in equation 4, and then used to compute phasing errors for a target nominal density for 0.05 kg/km^3 using equation 6, varying the location of PLM-2 (N) between 10 and 80 orbits before the encounter, yielding the spread of results shown in Figure 3. Because some instrument checkouts needed to be completed at the target density before the encounter observations began, anything later than 50 orbits was unacceptable, indicating both that drag needed to be considered in the PRM-2 design, since the mean variations were far from the two minute desired precision, and that PRM-3 would need to be placed after PLM-2 to allow the phasing correction to be done with knowledge of the approximate mean scale factor.

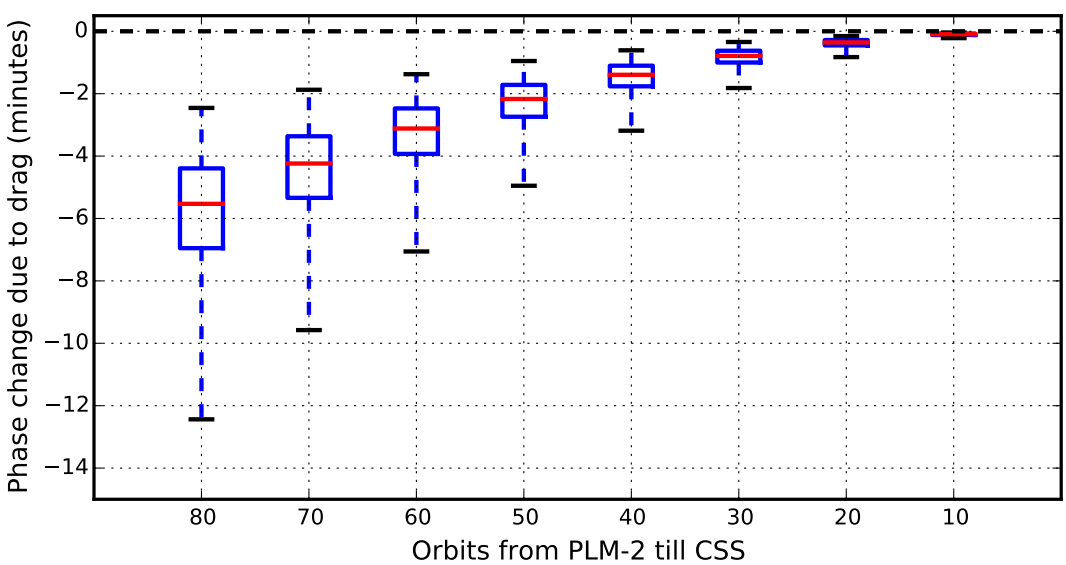

Figure 3. Statistics of phase change due to uncorrected drag errors

To understand how well PRM-3 could correct these drag errors, it was necessary to perform Monte Carlo scenarios re-targeting PRM-3 based on post-PLM-2 scale factor data. To do this, sample of scale factors and densities were computed as before. An estimated scale factor was generated by taking an average of the sampled values up to three orbits before the PRM, representing a 15 hour data cutoff time (DCO), and then designing the PRM to correct the difference in phasing (i.e. the accumulated time differences due to drag) between the nominal density and the estimated density. The achieved actual phasing was then computed by summing the truth density along with the accumulated phase change due to the period change from PRM-3. Performing these computations for 100,000 samples with PLM-2 at 30, 50, and 70 orbits before the encounter, and PRM-3 occurring in a range from five orbits after PLM-2 to five orbits before the encounter, as shown in Figure 4 demonstrated that PRM-3 was capable of correcting the errors successfully, that an early PLM-2 was acceptable, and that the PRM-3 placement derived from the simple period-accumulation mode was also acceptable.

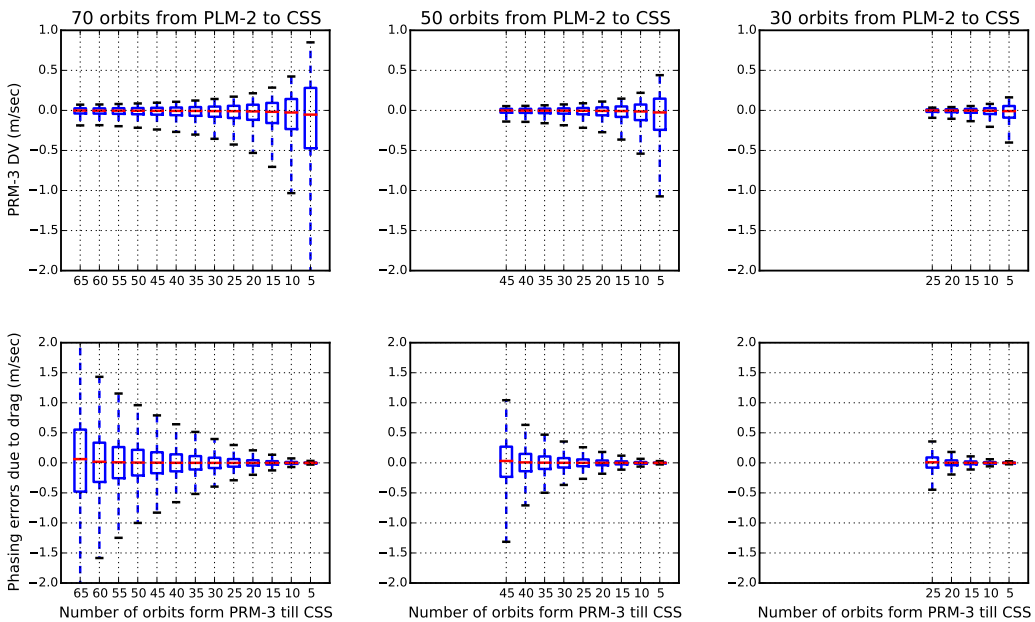

Figure 4. PLM-2 and PRM-3 parametric study statistics

III.C. Combined conic/drag model

Based on the previous two stand-alone analyses, the plan specified in Section II.B was formulated, with specific dates selected for operational convenience and to leave time for desired checkouts. However, these analyses were low fidelity and could not capture any correlations between PRM sequence errors, the effects of PLM-2 and drag effects. A higher-fidelity model was formulated that included a conic propagation of period, altitude and phasing as a function of time, the applications of PLM-1 through PRM-3 including the logic of selection, phasing offsets for PRM-2, cancellations and execution errors, and a simple exponential model of the atmosphere. Executing Monte Carlo runs based on this model allowed the team to be satisfied that the maneuver plan was capable of achieving the desired goals.

The orbit was modeled as a purely conic orbit that allowed changes of the period and altitude via velocity-direction impulsive burns at periapsis and apoapsis, with the phase captured by an initial mean anomaly and the accumulation of period over multiple revolutions. The orientation of the orbit would not change significantly from the nominal within the expected regime, allowing these terms to be neglected. Thus it was possible to query the period and altitude (above a spherical surface, for simplicity) with the equations:

$$P(j) = P_0 + \sum_{j_i<j} \Delta P_i \tag{7}$$

$$h(j) = h_0 + \sum_{j_i<j} \Delta h_i \tag{8}$$

where P and h are the period and altitude, and P_0 and h_0 are the initial values. j is the fractional number of orbits since the first periapsis, such that $j = 2.5$ is the third apoapsis, and $j = 7.0$ is the seventh periapsis (excluding the first). Each maneuver is represented by a set of values $(j_i, \Delta P_i, \Delta h_i)$, so that the period and the altitude are each a time series with instantaneous changes at maneuvers. The maneuvers are applied via conic formulae, computing the velocity using the vis-viva equation at the specified periapsis or apoapsis, increasing or decreasing the value according to the applied Δv, and then computing a new period using the same formulae in reverse. For an apoapsis maneuver, these same values can be used to compute a semi-major axis change, and thus an altitude change; periapsis maneuvers have a zero altitude change. This can be used to apply both drag and maneuvers. The time t and the fractional orbit number j are related by

$$t - t_0 = \left(P_0 + \sum_{j_i < j} \Delta P_i \right) j - \sum_{j_i < j} \Delta P_i j_i. \tag{9}$$

Note that the conversion from j to t is straightforward, while the reverse requires each maneuver to be processed in sequence to determine the point where the argument $j_i < j$ ceases to be true. Finally, this also allows us to determine the mean anomaly at a specified date, important for the analysis of the phasing capability, using the formula

$$M(t) = \mod \left(M_0 + 2\pi j(t),\, 2\pi \right). \tag{10}$$

An exponential density model, based around a spherical Mars was used to account for drag and PLM targeting. The atmospheric density at a particular periapsis (ρ_i) can be computed from the altitude h_i and a sampled scale factor $\log \beta_i$ as

$$\rho_i = \log \beta_i \rho_0 \exp \left[-\frac{h_i - h_0}{H} \right] \tag{11}$$

where the reference density ρ_0 is 0.5 kg/km^3 at the reference altitude h_0 of 170 km. The scale height H at this altitude is assumed to be 10 km. The scale factor is sampled from equation 4 with an approximate set of Δt values, since the period will not change enough to cause a significant difference.

The Monte Carlo process proceeded in a few steps:

1. Sample the initial post-MOI period and altitude from cruise Monte Carlo results, setting the MOI periapsis to be orbit 0.
2. Generate an atmospheric scale factor sequence sample.
3. Apply drag from this sequence until the PLM-1 apoapsis, and then select PLM-1 by finding the maximum sized option from the menu that keeps the altitude above 200 km.
4. Apply this PLM-1 Δv at $j = 1.5$ with sampled execution errors based on the selected size.
5. Apply drag until the PRM-1 periapsis, and then apply the fixed 455 m/sec burn at $j = 3$ with sampled execution errors.
6. Apply drag until the PRM-2 epoch.
7. Design PRM-2 (including PLM-2) assuming a scale factor of one for all orbits, since no good data will be available at this point.
8. Apply PRM-2 with sampled errors, apply drag until PLM-2 and then apply that burn with sampled errors as well.
9. Generate an estimate of the scale factor by averaging the sampled scale factor between PLM-2 and the DCO for PRM-3, five orbits before the execution.
10. Target PRM-3 to achieve the required phasing using the predicted scale factor from the DCO forward.
11. Apply drag until PRM-3, apply the selected burn to the orbit with sampled errors, and then apply the sampled drag until the date of the CSS encounter.
12. Collect statistics for the size of each burn, the total Δv, the final period and the final achieved phasing error.

Collecting all of these statistics yielded the data in Figure 5. These showed that the plan was capable of achieving the desired phasing, while keeping the period in a reasonable range, and keeping all maneuvers to a reasonable size. Generating similar statistics with the same models for the baseline plan allowed a comparison of Δv costs and showed a maximum 99% cost of 4 m/sec, and a median cost of only 0.5 m/sec, once the fuel required for future period corrections was included. The delay of the start of the science phase by 10 days was unavoidable, but the additional science collection around the comet encounter helped make up for the lost time. Ultimately these simulations helped demonstrate that the plan was viable and could be implemented.

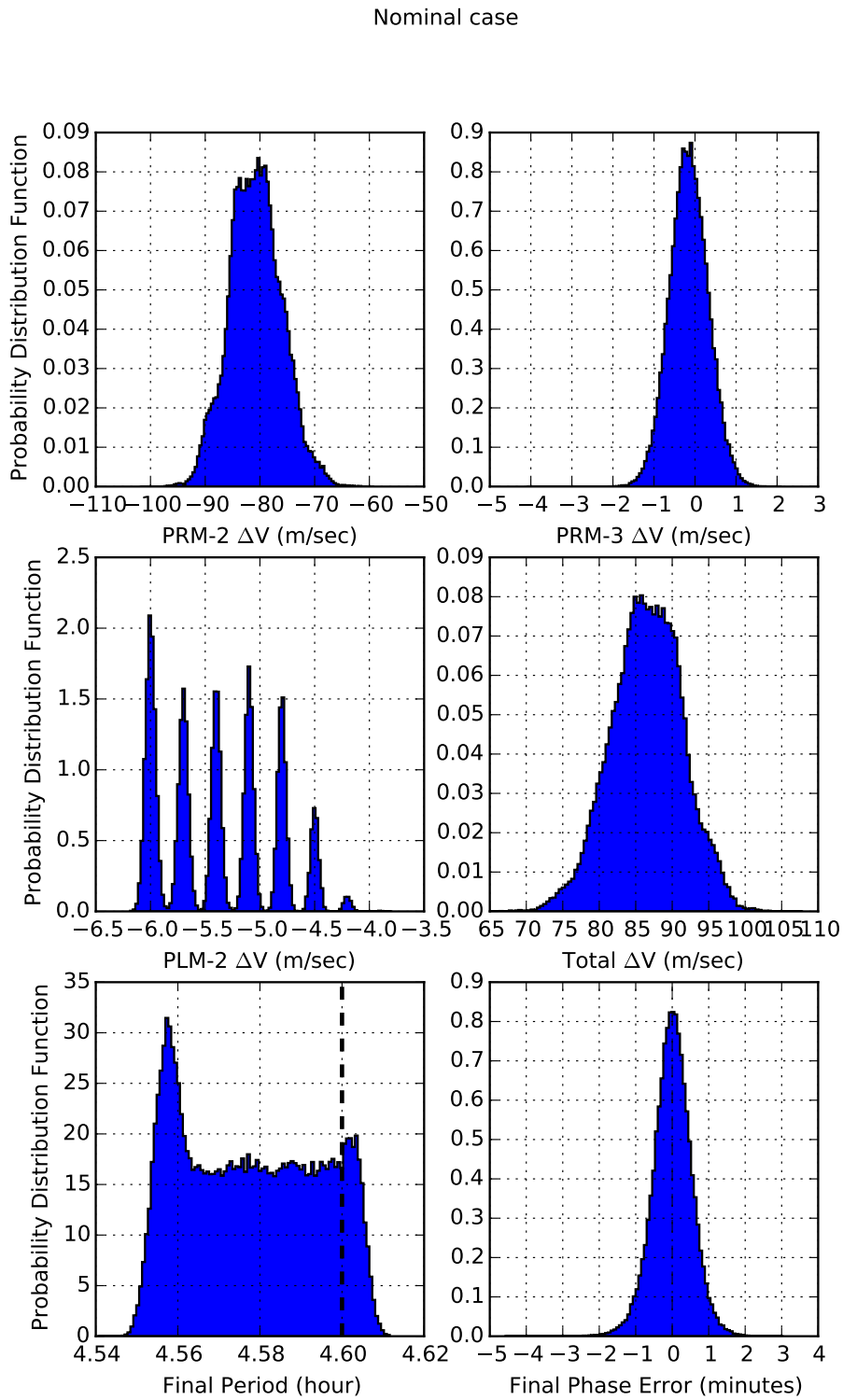

Figure 5. Full Monte Carlo statistics

IV. Operational Experience

The 33.2 minute long Mars Orbit Insertion (MOI) occurred as scheduled on Sept. 22, 2014, starting at 01:38 UTC. MOI decelerated the spacecraft into a 35.02 hour orbit with a 382.3 km periapsis altitude above the Martian spheroid. This was extremely close to the targeted orbit, with only a total 0.2σ offset from the nominal given the expected execution error model. From this orbit, the 8.0 m/sec option was selected for PLM-1, executing 1.5 orbits after MOI at Sept. 24, 2014 06:31 UTC and lowering the altitude to 204.6 km.

PRM-1 was scheduled to occur on Sept. 26, 2014 at 10:47 UTC, as an 8.7 minute long, 455 m/sec pitch-over burn centered about periapsis. While the maneuver sequence had been designed well before MOI, the start time was updated by 2.7 minutes based off of post-PLM-1 orbit determination solutions to account for small variations in orbit period. PRM-1 was to be executed on the main engines, which were only also used for MOI and the calibration for the first cruise maneuver, TCM-1. Technical difficulties related to the implementation of a new burn so soon after MOI caused PRM-1 to abort as soon as it began. Fortunately, the cause of the abort was discovered quickly and corrected, and the sequence was already designed to handle a timing update, so it was easy to re-schedule the maneuver for one orbit later, on Sept. 27, 2014 at 21:39 UTC. PRM-1 executed as expected and reduced the period to 5.45 hours, with an 11 sec, 0.06σ variation from the planned maneuver.

The day after PRM-1 executed and the post-maneuver orbit could be computed from the incoming Doppler data, the design of PRM-2 began. PRM-2 was designed by first targeting the 4.63 hour period, then selecting a PLM-2 from the menu that targeted the desired density level, and finally re-targeting PRM-2 (accounting for PLM-2 and drag effects) to the desired phasing target. Note that this targeting directly computed the original definition of phasing target, centering the occultation with respect to the vector of the maximum particle flux, rather than use the simplified mean anomaly target, which could have drifted slightly; this was made straightforward by the Monte navigation software used for operations.[7] A 79.2 m/sec, 15.7 minute long PRM-2 was designed, assuming a 2.7 m/sec PLM-2, and executed at periapsis 27, as a pitch-over starting from velocity direction on Oct. 2, 2014 at 21:22 UTC, and executed very precisely, getting within 0.2 sec (0.01σ) of the target period.

At arrival, the atmosphere was higher than expected, so a somewhat reasonable scale factor estimate of 3.5 could be seen and estimated in the Doppler data at the time of PLM-2. Based on this, PLM-2 was reconsidered, and the size was reduced to 2.55 m/sec in the anti-velocity direction. Because the spacecraft was not yet operating in the science configuration, it was actually built as a unique sequence rather than the standard OTM block that was originally planned, allowing a non-standard Δv, and the modification was found to more precisely target the desired phasing as well as the 0.05 kg/km^3 density target. It executed as planned, dropping the altitude to 179.9 km.

Following PLM-2, the navigation team began to experience more significant drag, and was better able to estimate the mean scale factor in preparation for PRM-3 targeting and to prepare for the post-comet density targets. The first 13 orbits showed that the mean density was approximately 80% of the pre-PRM-2 assumption, with the scale factor reduced to 2.9. Using this mean value to predict the trajectory at the comet encounter, the phasing error was determined to be only 0.5 minutes, less than the 2 minute limit specified by the project, and 0.01σ given the pre-MOI uncertainties. Based on this, it was decided to cancel PRM-3 and begin instrument checkouts in preparation for the comet encounter.

The comet encounter proceeded as planned. Variations in drag from the prediction drifted only 0.1 sec in timing, so that the achieved precision was only the 0.5 minute variation accepted while canceling PRM-3. Science observations were taken to produce valuable results,[8] and the instruments were shut down during the closest approach. Post-encounter checkouts revealed no damage to the spacecraft. Following the two days of post-encounter science observations, the spacecraft proceeded to perform checkouts and wait for the atmosphere to settle before selecting PLM-3.

PLM-3 was selected as a 2.7 m/sec DOWN maneuver, targeting the density to 0.12 kg/km^3. At this point the spacecraft was within the desired density corridor, and benign conditions allowed PLM-4 and OTM-0 to be canceled.

The final achieved orbit after PLM-2 met the phasing requirements within 0.5 minutes, with a period at the PRM-3 epoch of 4.62 hours, an altitude of 181.3 km, and total Δv for PLM-1 through PRM-2 of 542 m/sec, which compares favorably with the pre-launch 50% value of 546 m/sec. These show considerable more precision and finer targeting than the Monte Carlo results indicate, but this is well understood as a function of the maneuver execution errors being far more precise than modeled, the atmosphere being sensable before PLM-2 and also being particularly well-behaved, and PLM-2 being more precisely targeted

than was originally assumed to be possible. Table 3 shows the maneuver selections and achieved orbits for the entire transition phase.

Table 3. Executed maneuvers and achieved orbit shapes

Maneuver	Δv (m/s)	Final Period (hour)	Final Peri. Alt. (km)
MOI	1230.5	35.02	382.3
PLM-1	8.0	34.9	204.6
PRM-1	455	5.45	197.5
PRM-2	79.2	4.625	194.3
PLM-2	2.55	4.617	179.9
PRM-3	–	– *canceled* –	–
PLM-3	2.7	4.606	169.9
PLM-4	–	– *cancelled* –	–
OTM-0	–	– *cancelled* –	–

V. Summary

Before launch, the MAVEN operations plan after insertion into Mars orbit was to quickly reduce the periapsis altitude to 200 km using a pre-planned PLM-1, and then reduce the period from 35 hours to 5.5 hours using a pre-planned PRM-1, all within three orbits — five days — of MOI. A second periapsis burn, PRM-2, would then reduce the orbit period to the precise desired target a week later. Following this, a sequence of three menu-driven apoapsis burns, PLM-2, PLM-3 and OTM-0, each approximately a week apart would dip the spacecraft into the atmosphere, allowing the team to determine the approximate scale factor and target the density for the start of science operations on Nov. 1, 2014.

Upon the determination of more precise predictions of the trajectory and particle flux for Comet Siding Spring a few months after launch, this plan was modified to both use the bulk of Mars as a shield at the time of maximum particle flux, and to support unique opportunistic science observations of the interaction of the comet coma with the Martian atmosphere. These changes involved the re-purposing of PRM-2 to target the orbit phasing required for adequate shielding, the lengthening of the post PRM-2 time period to allow for science observations, spacecraft safety protections and additional checkouts, and the addition of a PRM-3 before the encounter to correct execution errors and drag effects, and fine-tune the timing of the orbit for adequate shielding.

The plan was implemented following a successful MOI on Sept 22, 2014. Despite an early issue with PRM-1, which was unrelated to the comet-related updates, the rest of the maneuvers proceeded as planned. Maneuver execution errors, which were significantly better than the pre-launch specifications, and a well-behaved atmosphere allowed PRM-3 to be canceled, and the desired orbit timing was achieved with an error of only 0.5 minutes. The mission was then able to proceed into the science phase.

The encounter with Comet Siding Spring so soon after the insertion into Martian orbit proved to be a unique challenge, requiring rapid re-planning for a deep space mission, and precise targeting during a time period with large maneuvers and imprecise orbit changes. This planning involved not just a re-targeting of maneuvers, but significant cooperation across the navigation, spacecraft systems and science operations teams to create a viable plan that met all needs and allowed the original post-transition mission plan to proceed with minimal degradation. The ability to run large-scale Monte Carlo simulations quickly was a major factor in determining that the plan was viable, and the same techniques may be useful for other tasks, possibly with modifications to allow for well-understood variations such as J_2/J_3 perturbations. Ultimately the experience demonstrated the capabilities and professionalism of the entire MAVEN team.

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