

TRANSFER TRAJECTORY DESIGN FOR THE MARS ATMOSPHERE AND VOLATILE EVOLUTION (MAVEN) MISSION

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The Mars Atmosphere and Volatile Evolution (MAVEN) mission will determine the history of the loss of volatiles from the Martian atmosphere from a highly inclined elliptical orbit. MAVEN will launch from Cape Canaveral Air Force Station on an Atlas-V 401 during an extended 36-day launch period opening November 18, 2013. The MAVEN Navigation and Mission Design team performed a Monte Carlo analysis of the Type-II transfer to characterize; dispersions of the arrival B-Plane, trajectory correction maneuvers (TCMs), and the probability of Mars impact. This paper presents detailed analysis of critical MOI event coverage, maneuver constraints, ΔV -99 budgets, and Planetary Protection requirements.

INTRODUCTION

The Mars Atmosphere and Volatile Evolution (MAVEN) mission will determine the history of the loss of volatiles from the Martian atmosphere to space and in so doing will determine the impact of this process on the climate, the habitability, and the presence of liquid water.^{1,2,3} MAVEN will achieve this by providing a comprehensive picture of the present state of the upper atmosphere and ionosphere of Mars and the processes controlling these regions from a highly inclined elliptical orbit.

MAVEN will launch from Cape Canaveral Air Force Station (CCAS) on an Atlas-V 401 during a unique extended 36-day launch period which opens November 18, 2013. The worst-case combination of injection energy (C3) and outbound declination provides a substantial mass margin for the launch capability. Upon arrival at Mars on September 22nd, 2014 (September 28th, for a nominal launch window close), MAVEN will perform a designed pitched-over capture maneuver with a nominal thrust of 1321N, imparting a delta-V (ΔV) of approximately 1233 m/sec over 36 minutes to achieve a 35-hr capture orbit at 75° inclination with a post-capture periapsis radius of 3779 km. Subsequent transition maneuvers will reduce the period to 4.5-hrs with the periapsis altitude within a required atmospheric density corridor of 0.05 kg/km³ to 0.15 kg/km³. A northern approach with a 5:45 pm local arrival time provides Earth visibility during the insertion burn.

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As part of the type-II transfer trajectory design, the Mars planetary protection requirements must be satisfied for any uncorrected injection error over the entire launch period. Using United Launch Alliance (ULA) injection correlation data produced using initial GSFC and JPL transfer trajectory designs, the MAVEN Navigation and Mission Design team performed a Monte Carlo analysis to characterize; dispersions of the arrival B-Plane, the trajectory correction maneuvers (TCMs) which eliminate these dispersions, and the probability of Mars impact to assess planetary protection considerations. The optimized TCM-1 will mitigate operational impacts but is constrained by a minimum 4-m/s ΔV magnitude at the first trajectory correction opportunity. This first correction maneuver is used to exercise the Mars Orbit Insertion (MOI) thruster assembly. Based on analysis and the maneuver constraint, a single B-Plane aim-point was chosen for the entire 36-day launch period.

Mission Overview

The MAVEN mission will be the first mission devoted to understanding the Martian upper atmosphere and addressing the compelling questions regarding its initial formation and subsequent evolution.^{4,5,6} These questions address the nature and history of Martian habitability by microbes, and how and why it has changed through time. As such, these questions fit cleanly into the Mars exploration program, whose broad goals include understanding the history of habitability and whether any organisms have ever existed on the planet. The MAVEN mission will explore the upper atmosphere of Mars and help scientists determine what role that loss of the atmosphere to space played in the history of the Martian atmosphere and climate. Over the last decade, data collected from many successful Mars missions support the view that liquid water existed at the surface early in Martian history. Increasingly, evidence points to loss of gases out the top of the atmosphere to space as an important, and possibly the dominant, process in the changing climate. Although recent measurements provide compelling evidence that loss to space has occurred, they do not allow a unique estimate to be made of how much gas has been lost, or to determine the specific processes by which the loss occurred.

MAVEN measurements can be considered from two different perspectives. From the perspective of the “science goals”, it will make three different types of measurements. First, it will determine the present-day composition and structure of the upper atmosphere. Second, it will determine the present-day escape rate of gas from the upper atmosphere to space. Third, it will make measurements that allow us to extrapolate this escape rate to past times, when the solar wind and the solar ultraviolet light (that drive the escape) were greater, to estimate the total amount of gas that has been lost.

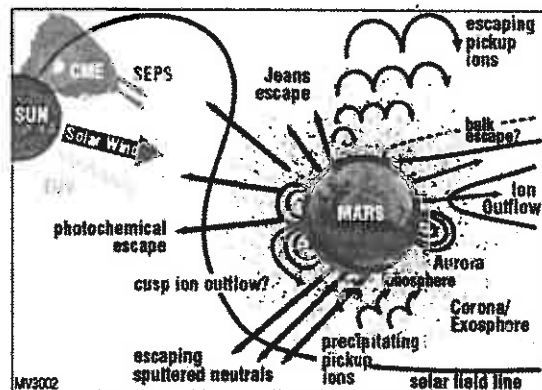


Figure 1. Mars Atmospheric Loss and Energy Processes Measured by MAVEN

From an “observational” perspective, MAVEN takes three types of measurements.^{5,6} First, it will measure the properties of the upper atmosphere as the spacecraft passes through the upper atmosphere on each orbit. These allow a very detailed look at one place in the atmosphere on each orbit, and allow determination of the basic state of the upper atmosphere. Second, it will make remote-sensing measurements of a large part of the planet from the high-altitude parts of its orbit. This will allow the point measurements to be extrapolated to global conditions, and will provide a good understanding of the geographical variations that can take place. Third, MAVEN will measure the energy inputs into the upper atmosphere that drive the processes that lead to escape. This will include the properties of the solar wind as it hits Mars, of solar ultraviolet light,

and of solar storms, all of which can affect the behavior of the top of the atmosphere. Figure 1 shows the different atmospheric loss and energy processes that MAVEN will measure. Neutral processes are shown in blue, ion and plasma processes in red, and solar energetic inputs are shown in the upper left.

Spacecraft Overview

The MAVEN spacecraft, shown in Figure 2, is the latest in a series of Lockheed Martin Mars orbiters to be developed for NASA (past orbiters include the Mars Global Surveyor, Mars Odyssey, and Mars Reconnaissance Orbiter (MRO)).⁵ Spacecraft features include redundant star trackers and Inertial Measurement Units (IMU); two 50-hour nickel hydrogen batteries; two fixed solar arrays; low-gain and high-gain antennas; a mono-propellant system; redundant Command & Data Handling system; and a fault-tolerant Mars Orbit Insertion (MOI) design. In addition, it is a 3-axis stabilized sun-pointing spacecraft, with a fixed high gain antenna. The spacecraft accommodates eight instruments (see Figure 3) that are segregated into three distinct packages: a Particles & Fields (P&F) package being developed by UC-Berkeley/Space Sciences Laboratory; a Remote Sensing Package being developed by CU-LASP; and the Neutral Gas and Ion Mass Spectrometer (NGIMS) being developed by GSFC.

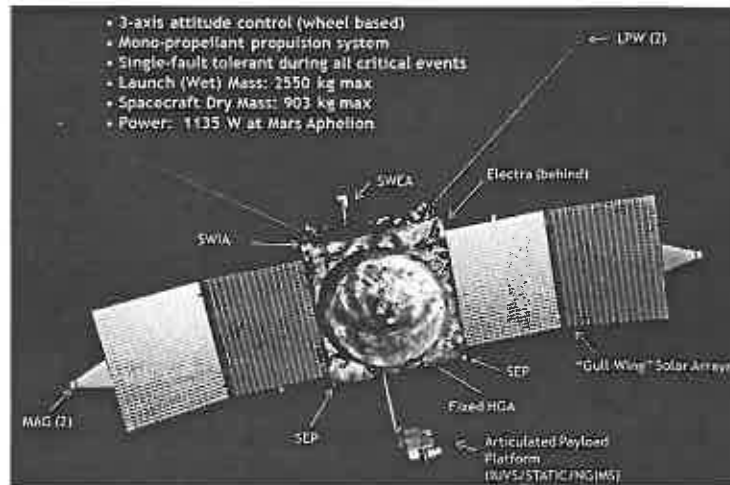


Figure 2. MAVEN Spacecraft

MAVEN TRANSFER TRAJECTORY DESIGN

MAVEN will launch from Cape Canaveral Air Force Station (CCAS) during a 36-day launch period (a 20-day nominal period with 16-days extended) opening November 18, 2013 on an ATLAS-V 401. The worst-case combination of injection energy and launch declination results in an allowable launch mass margin for the proposed 2354 kg current best estimate wet mass. Upon arrival at Mars on September 22, 2014 (September 28, for a Dec 7, 2013 nominal launch period close), MAVEN will insert into a capture orbit with a 35-hour period. Figure 3 shows the transfer trajectory and the dates of launch and arrival at Mars including the locations of all the planned TCMs. As with most planetary launches, there is a trade between the launch energy (C3), launch declination, and the arrival V-Infinity as these parameters vary over the launch period and they can become the driver for the mission design and propulsion system selection.

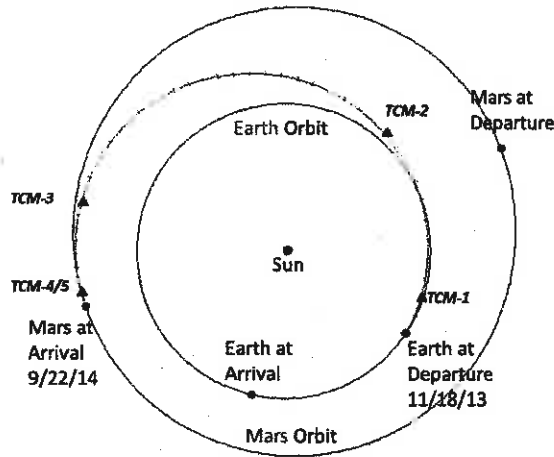


Figure 3 MAVEN Type - II Ballistic Transfer

MOI ΔV determined from V-infinity determines the close of the launch period. The launch declination remains under 28 degrees over the nominal launch period and thus does not pose a concern for reduced mass capability. Table 1 provides launch period information for the MAVEN mission.

For MAVEN, a change in arrival date by a week can result in an increase in the arrival V-infinity without a significant change to C3. The increased V-infinity yields an increase in MOI ΔV of ~ 50 m/s. Since the propellant tank is full, a late arrival scenario is highly unfavorable as there is no additional propellant margin. Figure 4 shows contours of the C3 and V-Infinity for the desired launch period. One can see in Figure 4a that the C3 over the launch departure dates are relative flat and decrease over the period by $2.6 \text{ km}^2/\text{s}^2$. The V-Infinity in Figure 4b however, has only a short duration where it remains flat near the minimum of 3.17 km/s . With a decreasing C3 over the launch period, the

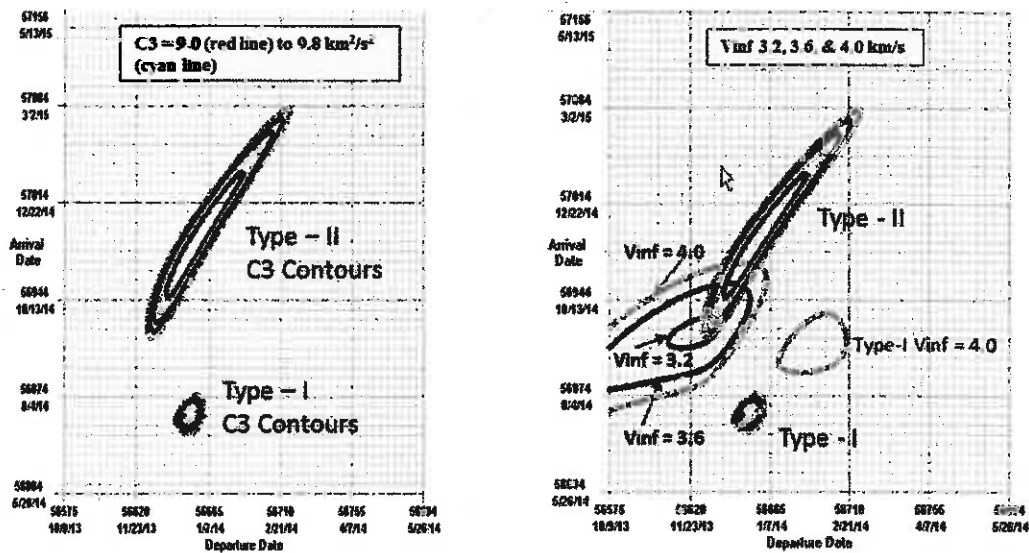


Figure 4 (a) and (b). C3 and C3 / V-Infinity Contour Plots

Table 1: Analytical Launch Period Parameters

| <i>Launch Period</i> | <i>Open</i> | <i>Mid</i> | <i>Close</i> |
|---|-------------|------------|--------------|
| C3 (km^2/s^2) | 12.07 | 10.30 | 9.40 |
| Declination (deg) | 13.38 | 18.84 | 26.93 |
| Right Ascension (deg) | 198.26 | 200.58 | 200.88 |
| Arrival date | 9/22/2014 | 9/24/2014 | 9/28/2014 |
| Arrival V-Infinity | 3.17 | 3.15 | 3.17 |

Selection of B-Plane Components

The selection of the target B-Plane begins with the completion of the determination of the ballistic type-II transfer. We initiated simulations using a full ephemeris and high fidelity environmental models to define transfer trajectories that propagated to the Mars periapsis. The B-plane components as defined in Figure 5 are computed at the epoch of the periapsis event. B-plane components are defined similarly to past Mars mission design references. The coordinates used for the B-Planes in this paper are based on the Mars Mean Equator IAU definition, with k being the Mars' North Pole. Note that the B.R negative direction is 'upward' and the B-angle increases in a counterclockwise direction.

The selection of the targeted B-Plane components is a result of several considerations. It must meet the planetary protection goals of less than $1e-4$ probability [reference 9] and meet the operational goal of a first TCM of 4 m/s minimum. This minimum ΔV is chosen so that the designed propulsion system can reach a steady state condition to successfully test the orbit insertion thrusters at an early portion in the transfer timeline. The current schedule has the first maneuver, TCM-1, occurring 15-days after injection. The chosen schedule permits time for navigation and other spacecraft operations to be completed.

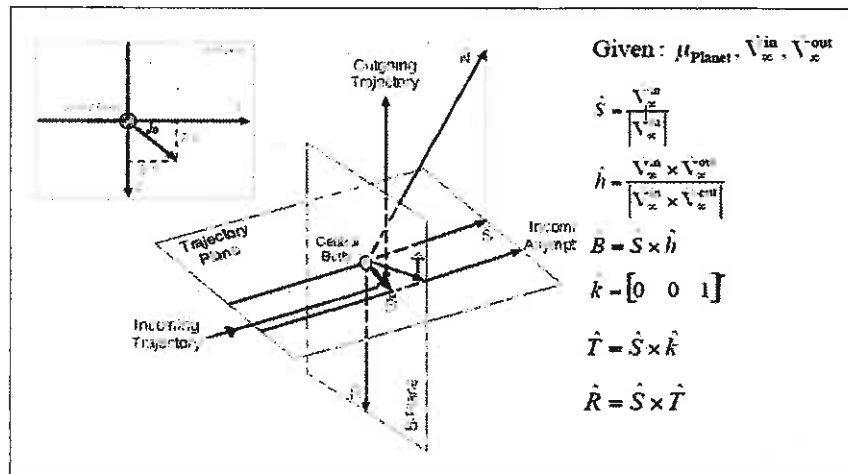


Figure 5. B-Plane Definition and Components

Transfer Injection Position State Generation

To obtain the initial states for our process, a simplified B-plane determination process was used and iterated with KSC and the Launch Vehicle Provider, ULA. Using high fidelity simulations with environmental models from all past Mars missions and estimates of the initial launch conditions, we targeted to the desired orbit insertion conditions. Starting with this information and an estimated TIP error matrix based on preliminary information exchanged with ULA, the direction of the maximum and minimum TCM-1 ΔV vectors can be computed for a preliminary estimate of the target B-Plane components that meets the planetary protection and TCM-1 ΔV requirement. From this iterated analysis, a selected B-Plane aimpoint was chosen with components of B.T = 16100 km, and B.R = -19300 km.

This aimpoint applies to the optimal condition of the daily launch window for the full launch period. For the first and second Configuration, Performance and Weight Status Report (CPWSR) delivery the B-Plane targets were held constant across the nominal launch period. Initial targeting simulations gave the results shown in Table 2 over the entire launch period. The table presents the

launch energy (C3) and outgoing asymptote angles of DLA and RLA for each date. Figure 6 shows the trending and the variation in C3, DLA, and RLA associated with discrete arrival times.

Table 2 – MAVEN Launch Information for Nominal and Extended Period

| Launch Opportunity | Launch Date | TIP Epoch (UTCG) | C3 (km ² /sec ²) | DLA (deg) | RLA (deg) | Launch Opportunity | Launch Date | Epoch (UTCG) | C3 (km ² /sec ²) | DLA (deg) | RLA (deg) |
|--------------------|-------------|------------------|---|-----------|-----------|--------------------|-------------|--------------|---|-----------|-----------|
| 1 | 11/18/13 | 20:38:56 | 12.23 | 12.78 | 198.26 | 21 | 12/08/13 | 16:55:11 | 9.31 | 26.72 | 200.45 |
| 2 | 11/19/13 | 20:32:25 | 11.98 | 13.24 | 198.52 | 22 | 12/09/13 | 16:39:48 | 9.30 | 27.42 | 200.87 |
| 3 | 11/20/13 | 20:25:33 | 11.73 | 13.72 | 198.78 | 23 | 12/10/13 | 16:04:21 | 9.35 | 28.50 | 200.84 |
| 4 | 11/21/13 | 20:18:22 | 11.50 | 14.24 | 199.03 | 24 | 12/11/13 | 15:23:36 | 9.41 | 29.60 | 200.83 |
| 5 | 11/22/13 | 20:10:48 | 11.27 | 14.80 | 199.27 | 25 | 12/12/13 | 17:29:38 | 9.53 | 30.88 | 200.85 |
| 6 | 11/23/13 | 20:04:30 | 11.08 | 15.24 | 199.61 | 26 | 12/13/13 | 17:04:34 | 9.66 | 32.07 | 200.89 |
| 7 | 11/24/13 | 19:57:54 | 10.89 | 15.70 | 199.94 | 27 | 12/14/13 | 16:49:49 | 9.73 | 32.83 | 200.93 |
| 8 | 11/25/13 | 19:48:51 | 10.69 | 16.39 | 200.16 | 28 | 12/15/13 | 16:37:08 | 9.91 | 34.09 | 201.01 |
| 9 | 11/26/13 | 19:38:42 | 10.49 | 17.17 | 200.33 | 29 | 12/16/13 | 16:32:00 | 10.02 | 34.97 | 201.07 |
| 10 | 11/27/13 | 19:32:03 | 10.33 | 17.57 | 200.58 | 30 | 12/17/13 | 16:46:16 | 10.14 | 35.67 | 201.14 |
| 11 | 11/28/13 | 19:21:30 | 10.15 | 18.28 | 200.57 | 31 | 12/18/13 | 16:43:00 | 10.27 | 36.46 | 201.21 |
| 12 | 11/29/13 | 19:11:02 | 9.98 | 18.96 | 200.63 | 32 | 12/19/13 | 16:19:06 | 10.55 | 37.82 | 201.35 |
| 13 | 11/30/13 | 18:59:48 | 9.84 | 19.75 | 200.70 | 33 | 12/20/13 | 16:30:25 | 10.73 | 38.64 | 201.43 |
| 14 | 12/01/13 | 18:47:36 | 9.71 | 20.57 | 200.76 | 34 | 12/21/13 | 16:36:01 | 11.10 | 40.10 | 201.62 |
| 15 | 12/02/13 | 18:37:33 | 9.60 | 21.18 | 200.89 | 35 | 12/22/13 | 16:26:48 | 11.05 | 40.04 | 201.52 |
| 16 | 12/03/13 | 18:23:27 | 9.50 | 22.02 | 200.90 | 36 | 12/23/13 | 16:25:50 | 10.91 | 39.69 | 201.38 |
| 17 | 12/04/13 | 18:13:23 | 9.42 | 23.02 | 200.90 | | | | | | |
| 18 | 12/05/13 | 17:56:42 | 9.37 | 23.99 | 200.98 | | | | | | |
| 19 | 12/06/13 | 17:38:13 | 9.33 | 24.99 | 200.85 | | | | | | |
| 20 | 12/07/13 | 17:23:17 | 9.30 | 25.69 | 200.88 | | | | | | |

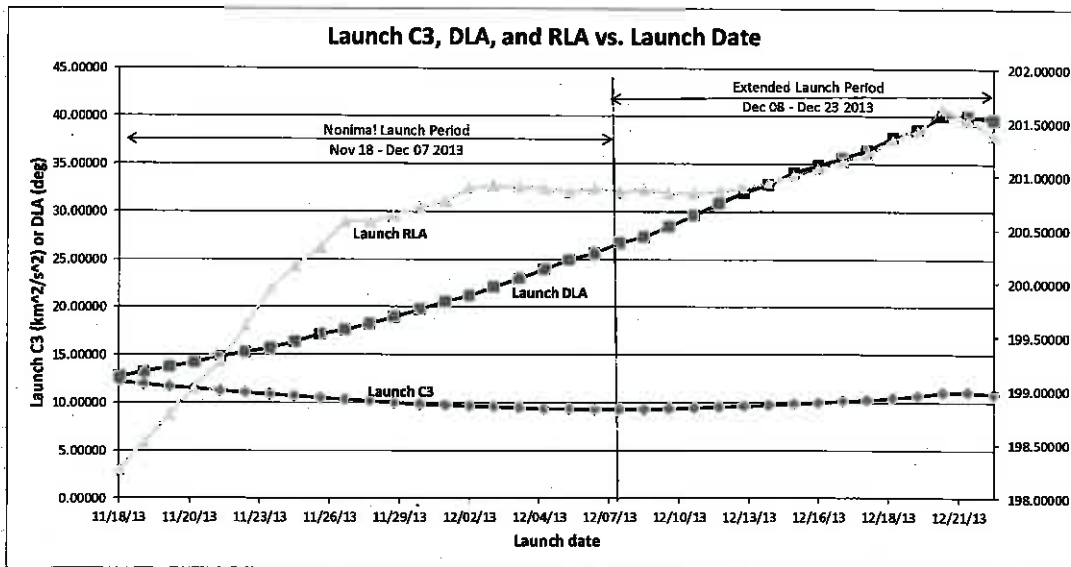


Figure 6. MAVEN C3, DLA and RLA over the Nominal and Extended Launch Period

Covariance Analysis Process

Covariance analysis of the type-II ballistic trajectory determines both the TCM ΔV budget and provides information on meeting the planetary protection requirements. Analysis began with the provided ULA Trajectory Injection Position (TIP) states. These states represent the post separation conditions without errors from the centaur injection. A set of figure of merit matrices was also provided with each state as part of the ULA CPWSR-1 delivery. We sampled a probability distribution associated with each eigenvalue and eigenvector by using the following procedure.

Monte Carlo analysis process

- Ingest correlation & covariance matrix in the RTN frame
- Multiply matrix for unit conversion (ft/sec to m/s) and copy covariance data to lower triangle
- Use initial simulation state (TIP state) to adjust Covariance matrix into EME2000
- Compute Eigenvalues and Eigenvectors using Matlab® 'eig' function
 - $[V,D] = \text{eig}(C)$ where C is the 6x6 error covariance
- Compute standard deviation (σ) using square root (sqrt) of eigenvalues. We assume that perturbations in each direction follow a zero-mean Gaussian distribution. The standard deviation (σ) of each distribution is.
 - $\text{std} = \text{sqrt}(\text{diag of } D)$
- Use Matlab's normally distributed random number generator with the standard deviation values to scale the random numbers for our application. We define a realization vector (δ), which is a change in the nominal injection state in Cartesian elements. This realization vector is found using;
 - $\delta = V * \tau$
- Where V is the 6x6 matrix and τ is a 6x1 matrix of the random numbers generated using the standard deviation values defined in (σ). This realization is added to the nominal Cartesian injection state and the injection epoch is defined as a constant value given by the ULA. That is to say, the off-nominal states are computed by addition of random errors to baseline state such that the new State = old state + error

[Note: In Matlab this is scripted as $dS(:,i) = \text{randn}(1,1)*\text{Std}(1)*V(:,1) + \text{randn}(1,1)*\text{Std}(2)*V(:,2) + \text{randn}(1,1)*\text{Std}(3)*V(:,3) + \text{randn}(1,1)*\text{Std}(4)*V(:,4) + \text{randn}(1,1)*\text{Std}(5)*V(:,5) + \text{randn}(1,1)*\text{Std}(6)*V(:,6);$]

- State is loaded into AGI's Astrogator® and used in propagation and/or targeting for 1000 samples

Covariance Analysis Results

The overall design process is to select the initial guess for a biased aimpoint (B.T, B.R) and determine the dispersion at Mars arrival epoch. In doing so, we produced an injection covariance to map the encounter analytically and generate a B-Plane covariance using Monte Carlo runs. We use a Probability Density Function (PDF) of a calculated distribution (assumed linear with aim-point) to determine the P[Impact] for a given aimpoint. From this we can then determine the ΔV required to correct a given aimpoint bias. The challenge for MAVEN is to find a B.T and B.R set that minimizes ΔV , constrained such that $\Delta V > 4$ m/s and $P[I] < 1e-4$. These

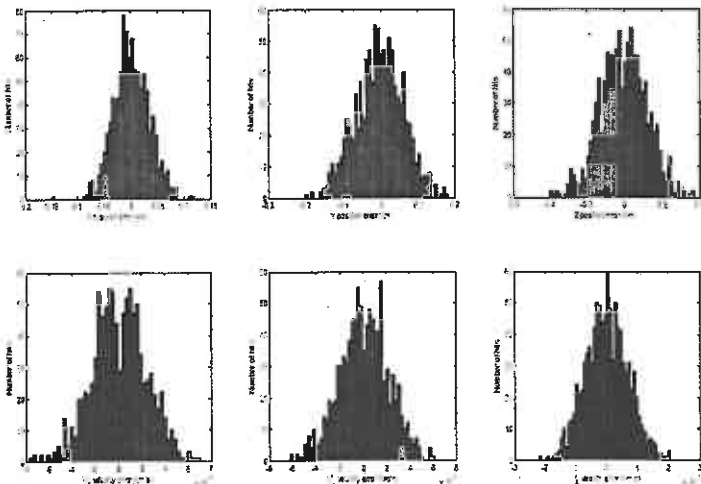


Figure 7. Sample Histogram of Post Injection Errors

constrained such that $\Delta V > 4$ m/s and $P[I] < 1e-4$. These

results were confirmed by independent verification between AGI's Astrogator Module and JPL's MONTE software as part of the standard MAVEN navigation support practice. Figure 7 shows a sample histogram of the generation of the errors on the TIP state using the above process. The figure shows the position and velocity errors in the EME2000 frame. Note that the 3-sigma errors in position are approximately 10 meters while the velocity errors are 15 m/s.

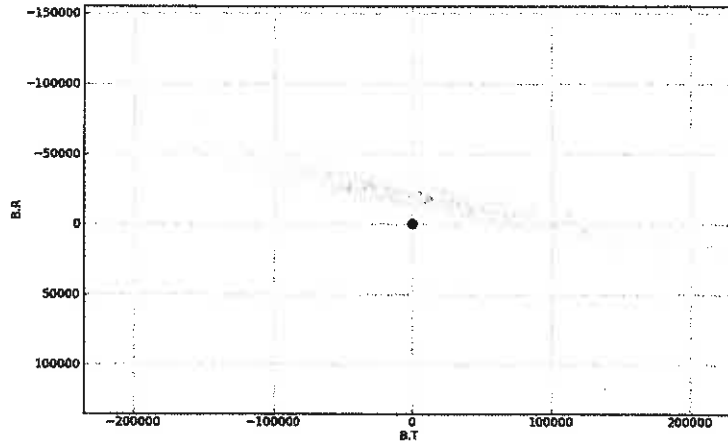


Figure 8 Sample B-Plane Distributions for Optimal Nov 28th 2013 Launch

Figure 8 presents a sample B-plane distribution for the MAVEN trajectory if launched at the opening. As seen the angle of the distribution for this launch opening case is near 12-deg and is a function of the launch date and the orientation of the relative orbit planes of Earth and Mars. From the initial states, with errors, the distribution of the B-plane components can be used to determine the PDF and therefore the probability of impact with Mars.

Probability of Mars Impact

Equations 1- 4 provide the background of the method used to compute the impact probability. Equation 1 shows the calculation of the 2-D Gaussian PDF. Equation 2 shows the probability of being in area $[A]$, and equation 3 shows the calculation of the 'B-Plane' area that would impact the Martian surface. Thus, impact probability can be calculated using equation 4.

$$f(\mathbf{a}) = \frac{1}{2\pi\sqrt{\text{Det}[\Sigma]}} \exp\left[-\frac{1}{2}((\mathbf{a}-\mu)^T \Sigma^{-1}(\mathbf{a}-\mu))\right] \quad (1)$$

$$P[A] = \iint_A f(\mathbf{a}) d\mathbf{a} \quad (2)$$

$$r_{mp} = r_M \sqrt{1 + \frac{2 \cdot GM}{C_3 r_M}} \approx 6462 \text{ km} \quad (3)$$

$$P[I] = \int_0^{r_{mp}} dr \int_0^{2\pi} d\theta (r \cdot f(r, \theta)) \quad (4)$$

Based on these equations and the data from the high fidelity simulations using AGI's Astrogator[®] (V9.2) and Matlab[®], the data shown below is generated. Figure 9 shows a sample of the probability of impact with the highlighted contours (blue) indicating the 1e-4 requirement.

Also shown is the 4 m/s TCM-1 ΔV magnitude (red) elliptical shaped contour to meet the insertion orbit requirements. Several choices can be made regarding the selection of the aimpoint that meets both requirements. Based on these data, impact and TCM-1 ΔV cost can be computed and compared across the launch period or launch day.

Launch Period B-Plane Distribution and Impact Probability

Following the procedures and equations shown above, Monte Carlo analysis was completed for the launch period opening, mid, close and an extended launch period date. This analysis represents the launch dispersion estimates for the CPWSR-1 delivery and is currently undergoing an update. As the analysis was completed it was recognized that the angle of the B-Plane distribution ellipses' semi-major axis with respect to the B.T direction (in the Mars orbit plane by definition), increased both as the launch date moved from launch opening to launch closure and also minimally across the daily 2-hour launch window. The major and minor axes amplitudes also varied over the period with an average of $2e5$ km and $2e4$ km respectively. The distribution geometry is a function of the angle between the Earth and Mars orbit planes, launch geometry, and launch injection errors.

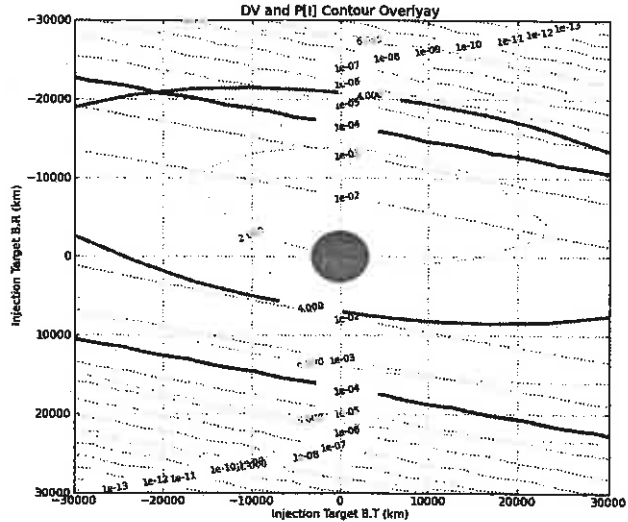


Figure 9. Combined Probability of Impact and TCM-1 ΔV (m/s) Magnitude

The next series of figures presents the B-plane distribution and related probability contours for launch open (Nov 18th), mid (Nov 27th), close (Dec 07th), and extended (Dec 15th) of the launch period. Also included is the effect of a 2-hr launch window for each launch date, as shown in the figures from left to right. For epochs between those shown, we found a linear effect. Figures 10 through 13 shows the B-Plane distribution for these launch dates while Figure 14 through 16 shows the probability of impact. Information for an extended launch date of Dec 15th is provided to show the continuation of the analysis for evaluation of launch dates past the nominal period end.

The Probability of Impact, $P[I]$, for the shown B-Plane distributions all meet the required $P[I] < 1e-4$. The way to interpret the probability plot contours is similar to the B-Plane plots. A small circle is shown that represents the nominal aimpoint which meets the $P[I]$ and TCM-1 ΔV requirements and also represents the targeted point for all ULA deliveries. The $P[I]$ contour lines represent the probability of impact of each possible B-Plane aimpoint on the figure based on equations 1-4 with the mean being the center of the distribution and r_{imp} being the impact radius. Figure 17 shows the probability of impact over the entire launch period and that the least favorable $P[I]$ occurs at the launch opening.

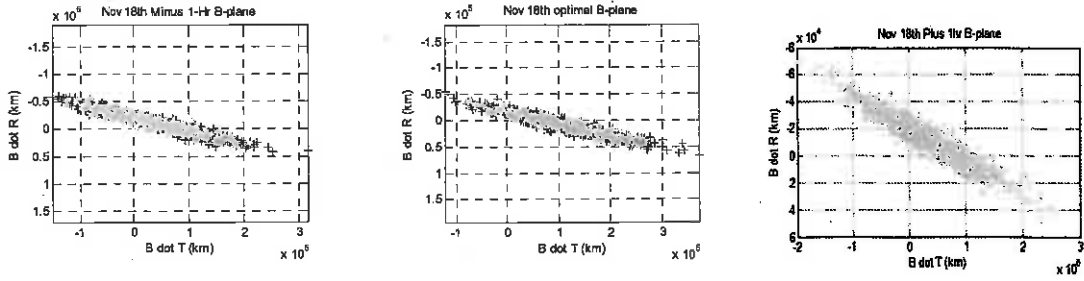


Figure 10. B-Plane Distribution for Launch Open, Nov 18th 2013, with 2-hr window

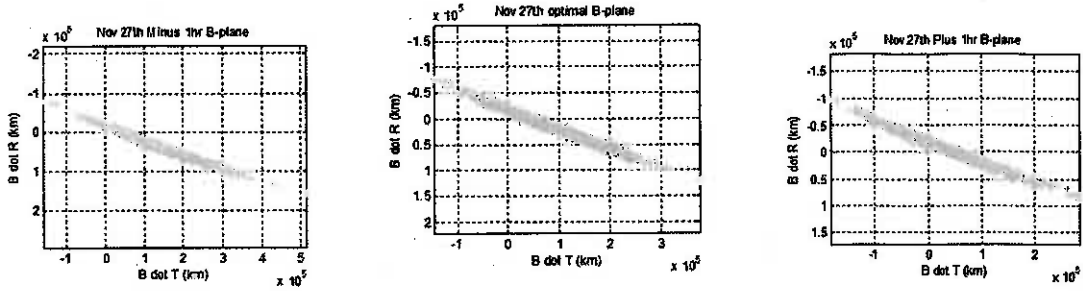


Figure 11. B-Plane Distribution for Launch Mid, Nov 27th 2013, with 2-hr window

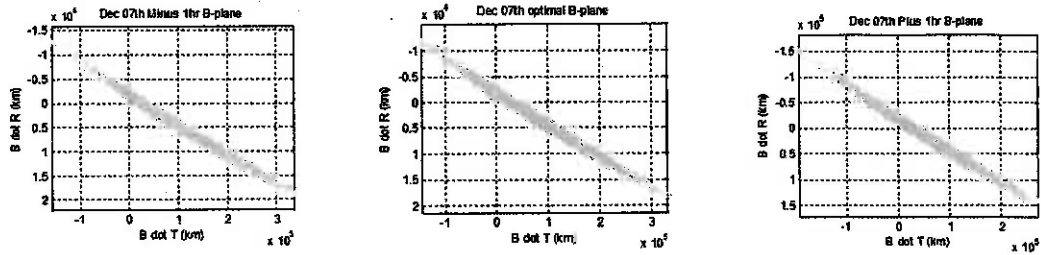


Figure 12. B-Plane Distribution for Launch Close, Dec 07th 2013, with 2-hr window

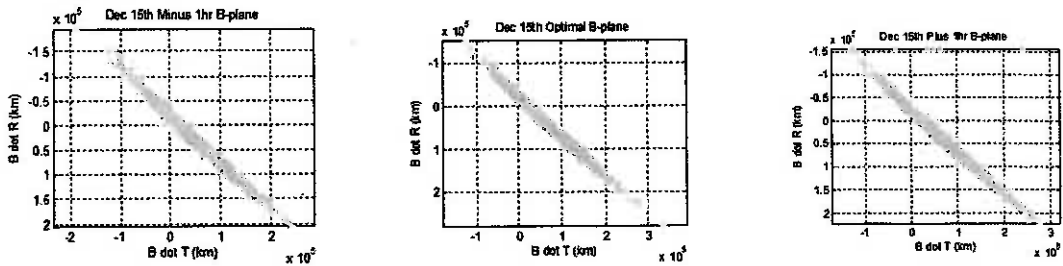


Figure 13. B-Plane Distribution for Launch Extended, Dec 15th 2013, with 2-hr window

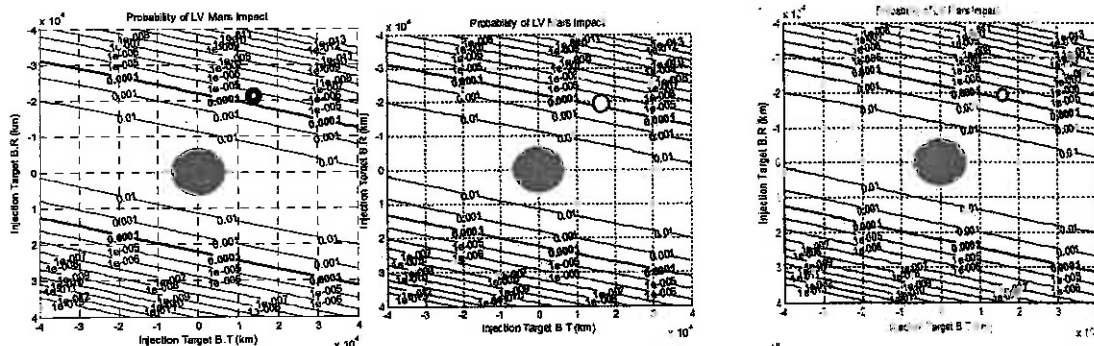


Figure 14. B-Impact Probability for Launch Open, Nov 18th 2013, with 2-hr window

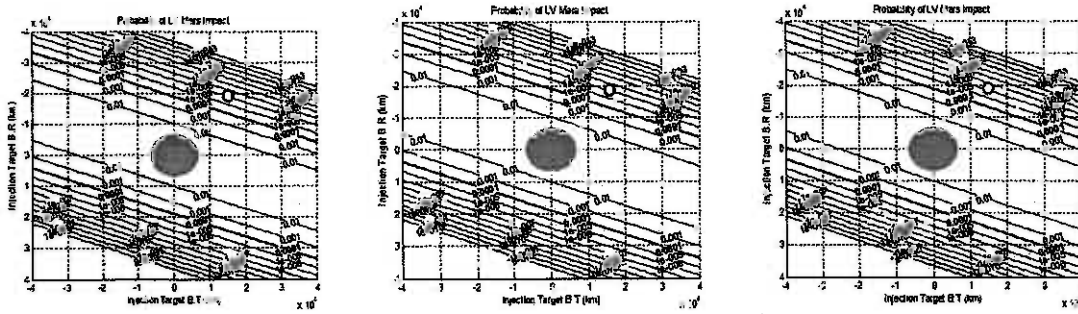


Figure 15. B-Impact Probability for Launch Mid, Nov 27th 2013, with 2-hr window

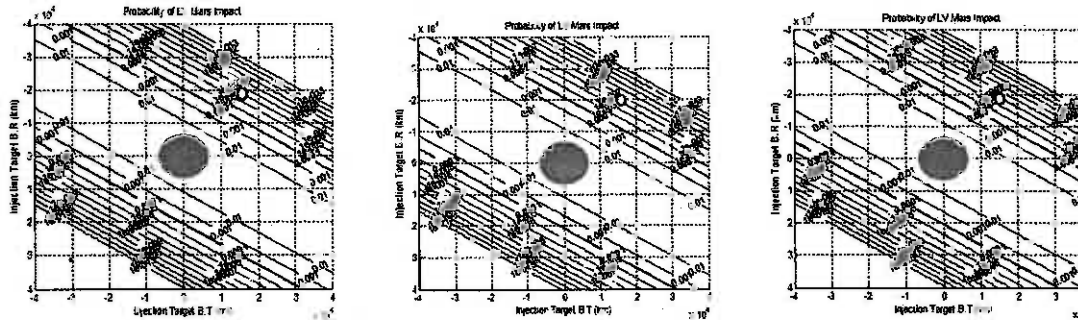


Figure 15. B-Impact Probability for Launch Close, Dec 07th 2013, with 2-hr window

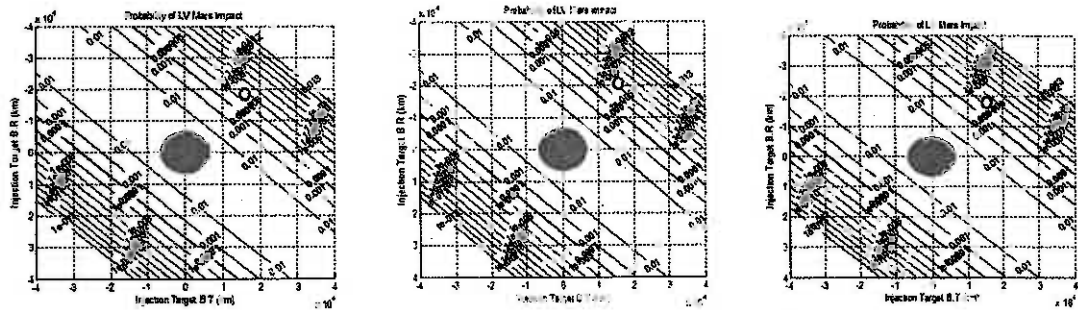


Figure 16. B-Impact Probability for Launch Extended, Dec 15th 2013, with 2-hr window

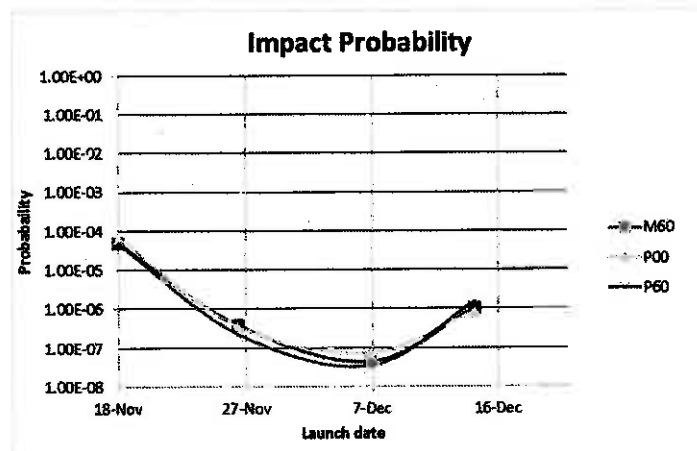


Figure17. Impact Probability over Launch Period

TCM-1 ΔV Statistics

With the B-Plane distribution statistical analysis completed, we determined the TCM-1 budget for the transfer trajectory. For each of the cases provided above, the distribution of the TCM-1 ΔV performed at injection plus 15 days is shown. As can be seen the variation in the TCM-1 ΔV magnitude can be quite large, ranging from approximately 2 m/s to over 15 m/s depending on the launch date and the time of day of launch. Figures 18 through 21 show the TCM-1 ΔV magnitude (units of km/s) distribution for each launch condition corresponding to the above B-plane distribution and P[I]. Using the ΔV magnitude and MATLAB statistical functions (e.g. percentile, mean, median), Table 3 provides the statistical analysis of these plots and the 3-sigma and ΔV -99 for the nominal launch period. The extended launch period date of Dec 15th indicates a ΔV magnitude that approaches 50 m/s. While the ΔV magnitude is larger than the allowable TCM-1 ΔV budget of 20 m/s, it is still within family when considering the total ΔV budget and the desire to launch during the 2013 cycle. The epoch of TCM-1 can also be adjusted to vary the magnitude of the TCM-1 ΔV in order to maintain a minimum 4 m/s requirement.

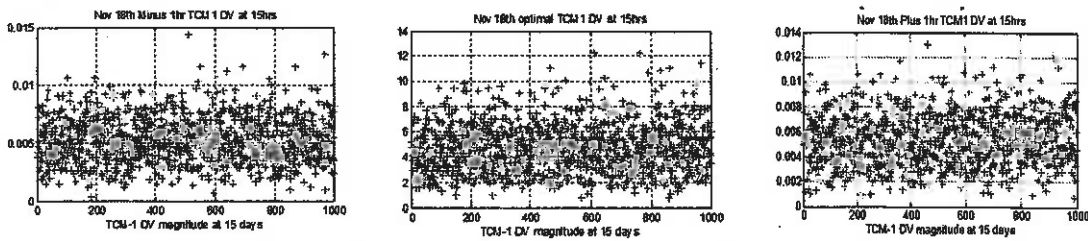


Figure 18. TCM-1 ΔV s for Launch Open, Nov 18th 2013, with 2-hr window

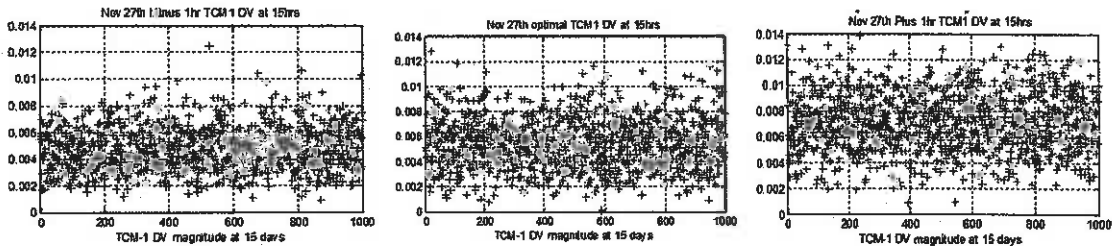


Figure 19. TCM-1 ΔV s for Launch Mid, Nov 27th 2013, with 2-hr window

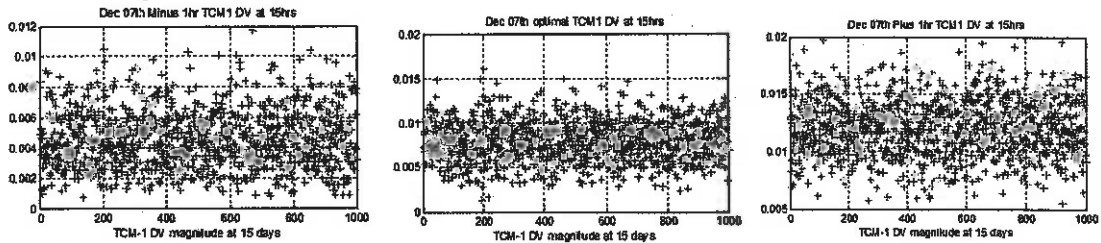


Figure 20 TCM-1 ΔV s for Launch Close, Dec 07th 2013, with 2-hr window

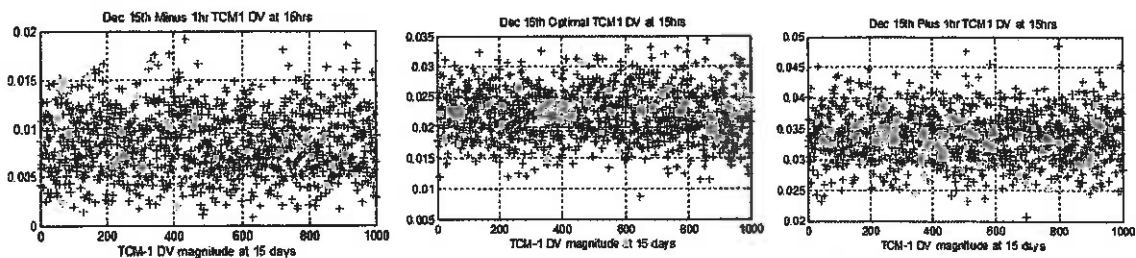


Figure 21 TCM-1 ΔV s for Launch Extended, Dec 15th 2013, with 2-hr window

Table 3. TCM-1 Statistical ΔV Information

| Launch date and window | Max (m/s) | Min (m/s) | Mean (m/s) | Std (m/s) | 3-sigma (m/s) | DV-99 (m/s) |
|------------------------|-----------|-----------|------------|-----------|---------------|-------------|
| Nov 18 Minus 1hr | 9.6 | 1.2 | 4.9 | 1.2 | 8.6 | 7.9 |
| Nov 18 Optimal | 12.8 | 1.7 | 5.5 | 1.5 | 10.1 | 9.6 |
| Nov 18 Plus 1hr | 12.9 | 2.4 | 6.6 | 1.8 | 11.9 | 11.2 |
| Nov 27 Minus 1hr | 9.9 | 2.1 | 5.4 | 1.2 | 9.0 | 8.6 |
| Nov 27 Optimal | 13.0 | 2.3 | 6.4 | 1.7 | 11.4 | 10.5 |
| Nov 27 Plus 1hr | 15.1 | 2.7 | 8.2 | 2.0 | 14.1 | 13.0 |
| Dec 07 Minus 1hr | 11.1 | 1.8 | 5.7 | 1.5 | 10.3 | 9.7 |
| Dec 07 Optimal | 15.5 | 3.8 | 8.9 | 1.9 | 14.6 | 13.4 |
| Dec 07 Plus 1hr | 20.3 | 6.8 | 13.1 | 2.3 | 20.0 | 18.6 |

ADDITIONAL DESIGN CONSIDERATIONS

Modeling and Optimization

The environmental models used for the analysis presented above are representative of all previous Mars missions and the MAVEN Mission Design and Navigation team has thoroughly verified consistent and accurate trajectory designs using both the AGI Astrogator V9.2 and JPL's MONTE software. As part of the ongoing analysis the team is well aware that optimizing a combination of TCM-1 ΔV at 15-days after launch with the TCM-2 ΔV performed 90 days after launch would benefit the overall TCM budget as well as permit more operational options. The TCM-1 in this optimization process could be held to the required 4 m/s magnitude.

Orbit Plan Angle

As seen in several figures, the slope (angle wrt the B.T direction) of the B-Plane distribution ranges from ~11-deg to ~45-deg over the launch period. This angle plays an important function in the magnitude of the TCM-1 ΔV s. The importance of the distribution is in the TCM ΔV s to correct the trajectory from the biased aimpoint back to the required insertion conditions. The ΔV s are minimal in the B.T direction as that direction is a heliocentric orbit period correction. The ΔV to change the B.R direction is larger as it is associated with a heliocentric inclination or arrival declination change. Also the location of the TCM-1 maneuver is not optimal wrt to inclination changes nor represents an optimal broken plane maneuver. With the opening launch date arrival conditions, the heliocentric inclination is ~ 2-deg and increases nearly 1-deg towards the launch closure date. The Mars incoming declination varies from -20-deg at opening to -33-deg at closure.

MOI constraints

As part of the various rules and goals with respect to observation of critical events, the timing of the MOI and the targeted Mars arrival epoch was controlled such that two independent DSN sites could maintain coverage of the complete MOI duration. This is a straight forward targeting strategy in that the arrival epoch of Mars periapsis is targeted in the overall design process. This arrival time is dependent upon the dual coverage of both Canberra and Goldstone DSN sites for MOI and is centered at 02:00 hrs. Since the MOI maneuver is approximately 36 minutes in duration, even with fault tolerant measures in place, this dual coverage permits either site coverage throughout the maneuver. Other launch period dates are similar since the arrival time is

fixed and any launch injection or navigation errors can be fixed with small correction maneuvers of approximately 10 cm/s in magnitude.

CONCLUSION

We have described the methodology that was used to perform the MAVEN injection dispersion analysis. This methodology includes running a Monte Carlo analysis based on a single injection opportunity that can be assumed to be independent of other errors and is considered the baseline mission design case. From this analysis we confirm that the MAVEN project budgets 20 m/s for the TCM-1 ΔV that is performed at 15-days after injection for 3σ injection dispersions. This recommendation is equivalent to the 3σ of the TCM-1 magnitude ΔV with a 50% margin at launch period opening and 25% margin at launch period close. Changes to the MOI maneuver are negligible with respect to the results of the Monte Carlo analysis. The TCM-1 ΔV magnitudes depend upon the specific Atlas-V 401 covariance matrix delivered. The analysis presented will be repeated using ULA CPWSR-2 and CPWSR-3 data for a definitive MAVEN ΔV budget.

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