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MARS ATMOSPHERE AND VOLATILE EVOLUTION (MAVEN) MISSION DESIGN

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The Mars Atmosphere and Volatile EvolutioN (MAVEN) mission was selected as the second in the low-cost Mars Scout mission series. MAVEN will determine the role that loss of volatiles to space has played through time from a highly inclined elliptical orbit. The launch period opens November 18, 2013 with arrival September 16, 2014. After achieving a 35-hr capture orbit, maneuvers will reduce the period to 4.5-hrs with periapsis near 150 km and maintain the periapsis within a specified density corridor. MAVEN will also execute "Deep Dip" campaigns, with periapsis at an altitude near 125 km. This paper presents the unique mission design challenges of the MAVEN mission.

INTRODUCTION

Selected by National Aeronautics and Space Administration (NASA) Headquarters in 2008 as the second Mars Scout mission, Mars Atmosphere and Volatile Evolution (MAVEN) is a Principal Investigator-led mission with project management responsibility assigned to the Goddard Space Flight Center (GSFC).[1,2] The mission is scheduled for launch in November 2013 and will reach the red planet in September 2014. Once in orbit around Mars, with a baseline one-Earth-year mission, MAVEN will study the current Mars upper atmosphere, solar interactions, and the loss of volatiles from the atmosphere to space. MAVEN will determine the role that loss of volatiles to space has played through time, determining the histories of the atmosphere and climate, liquid water, and habitability. The MAVEN mission continues the "follow the water" theme that has been the cornerstone of Mars scientific study over the past decade.[2] MAVEN will provide 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.

Science Overview

The MAVEN mission will be the first mission devoted to understanding the Martian upper atmosphere and addressing the compelling atmosphere questions.[3,4] 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.

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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.

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.

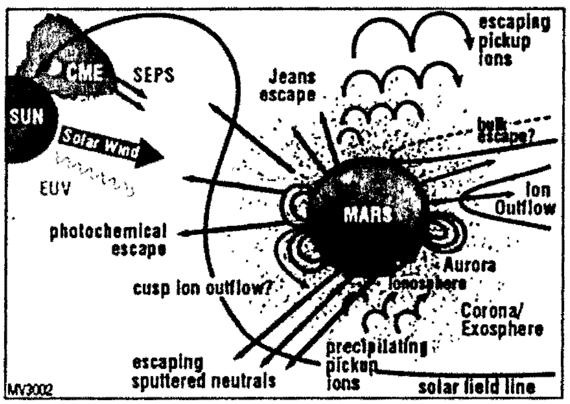


Figure 1. Mars Atmospheric Loss and Energy Processes Measured by MAVEN

Instruments

The eight instruments flown onboard MAVEN will be built by three different institutions and delivered to Lockheed Martin for integration.[5, 7] Two instruments will be built at the Laboratory for Atmospheric and Space Physics at the University of Colorado (CU-LASP), four will be built at the Space Sciences Laboratory of the University of California at Berkeley, and two will be provided by NASA's Goddard Space Flight Center (GSFC). The instruments that are used within the atmosphere have requirements on the density though which they will fly. For this reason, a density corridor has been defined and is shown in Table-1.

In addition to providing two instruments, GSFC is responsible for managing the MAVEN mission under the direction of the Principal Investigator. This management includes providing system engineering and subsystem and instrument leads. The mission design support is led by the

Navigation and Mission Design Branch, Code 595, at GSFC. NASA's Jet Propulsion Laboratory (JPL) will provide tracking and navigation support and communications through its Deep Space Network (DSN). Mission operations will be conducted by Lockheed Martin in Denver, with science operations at the CU-LASP. A backup mission operations center will be housed at Goddard. The science team and science analysis will be distributed, with each instrument team staying predominantly at its home institutions.

Table 1. MAVEN Periapsis Density Corridors and Limits

Mission Segment	Mass Density ($kg.km^3$)	Ambient Pressure (torr)	Dynamic Pressure (torr)	Number Density (part/cc)
Nominal Top	**0.05**	**2.06e-8**	**3.21e-6**	**6.6e+8**
Nominal Bottom	0.15	5.22e-8	9.71e-5	1.67e+9
Deep Dip	**2.0**	**4.8e-6**	**1.3e-4**	**1.54e+11**

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] MAVEN is based on the MRO design. Key features include redundant star trackers and Inertial Measurement Units (IMU); two 50-hour nickel hydrogen batteries; two fixed solar arrays; low-gain, medium 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. It is designed to be compatible with the current Evolved Expendable Launch Vehicle (EELV) configurations (Atlas V and Delta IV).

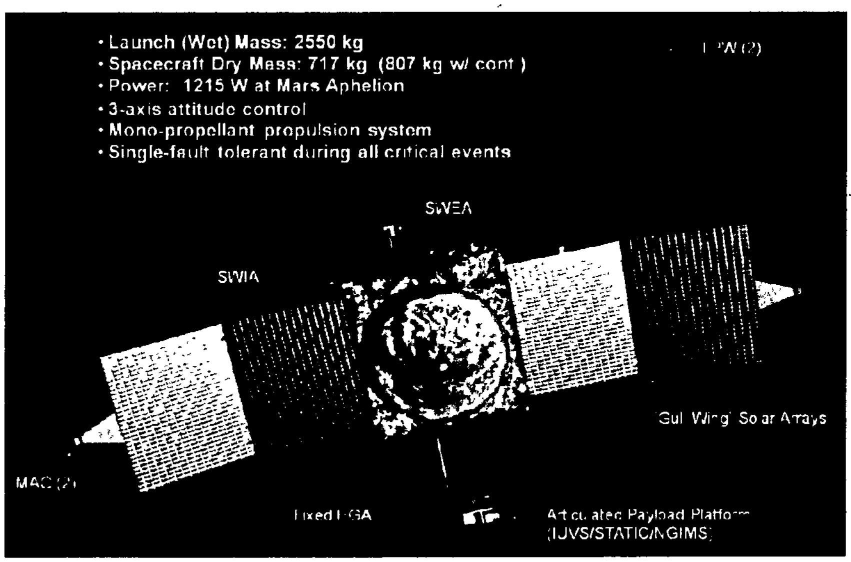


Figure 2. MAVEN Spacecraft

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.

The P&F package includes six of the eight MAVEN instruments: The Solar Wind Electron Analyzer (SWEA), the Solar Wind Ion Analyzer (SWIA), the Suprathermal and Thermal Ion Composition (STATIC), the Solar Energetic Particle (SEP), the jointly-built LASP and SSL Langmuir Probe and Waves (LPW), and the GSFC-built Magnetometer (MAG). The LPW system also contains an EUV monitor capability. The P&F package includes its own data processing unit. This package will focus on solar interactions, as well as provide a detailed understanding of the ionosphere and upper atmosphere.

The Remote Sensing Package contains a single instrument, the Imaging Ultraviolet Spectrometer (IUVS), and a data processing unit. This package measures the global characteristics of the upper atmosphere and ionosphere.

The NGIMS is a highly sensitive mass spectrometer that will measure the composition and isotopes of thermal neutrals and ions. The NGIMS package performs these types of measurements near periapsis (below 400 km altitude) and is the driver for the Deep Dips.

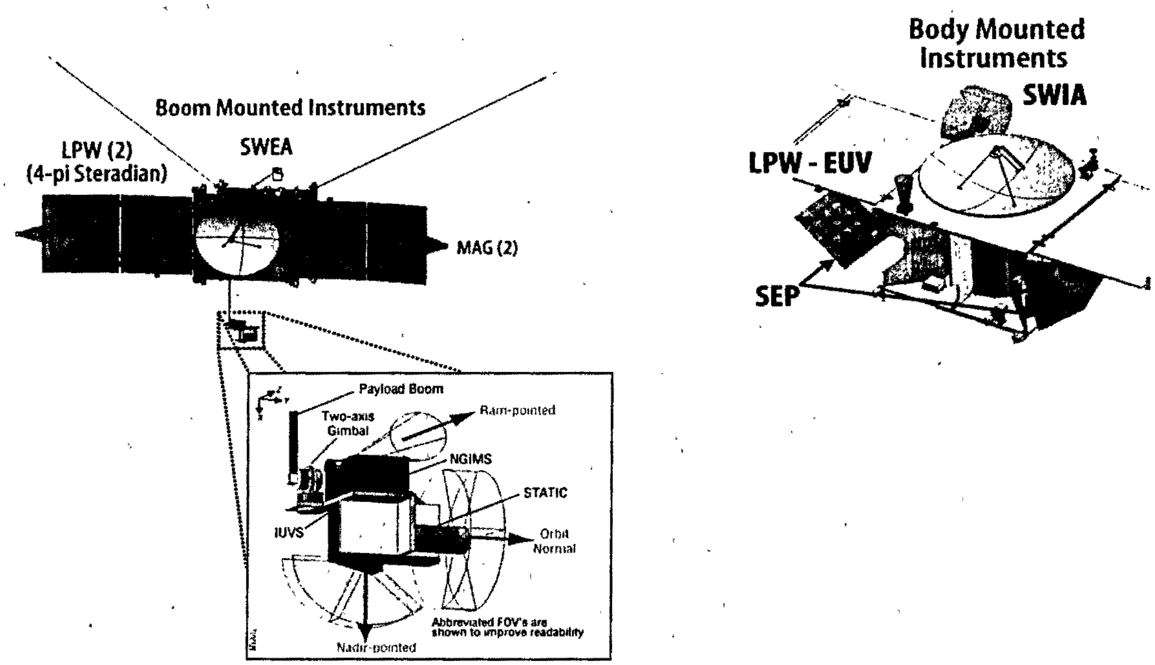


Figure 3. MAVEN Instrument Locations and Views

The complement of instruments is distributed on the spacecraft as body-mounted instruments (SWIA, EUV, SEP), boom-mounted instruments (LPW, SWEA), solar array-mounted instruments (MAG), and instruments mounted on an articulated payload platform (NGIMS, STATIC, IUVS). MAVEN will also integrate a JPL Electra communications package that will be able to serve as a relay for surface assets. This is the same function that Mars Global Surveyor, Mars Odyssey, and the Mars Reconnaissance Orbiter have carried out. The MAVEN team has been working with the Electra team and the Mars Program Office at JPL to ensure that the MAVEN spacecraft is capable of supporting and commanding Electra as needed. MAVEN will arrive at Mars when the Mars Science Laboratory, to be launched in 2011, is entering its extended mission, and MAVEN may be called on to serve as a relay for some of its data.

Mission Design Requirements and Challenges

The above science requirements and mission goals result in unique challenges for the MAVEN mission design. Table 2 shows how the driving science requirements and goals are mapped to the mission design parameters and maneuver constraints identifying associated unique challenge.[5]

Table 2. MAVEN Requirements and Challenges

Science Requirement or Goal	*Mission Design Parameters*	*Challenge*
Mission during solar cycle peak	Arrival during early 2010s, 20 day launch period	Limited launch window drive design, drives fuel cost and subsystem design
Primary science orbit shall provide access to all latitude and solar times	$a = 6578$km, $e=0.4608$, $i=75$deg,	Insertion Targets with an all Propulsive System, Maintenance, Tolerances
Enable measurements of solar wind, magnetic field, and bow shock	Apoapsis $\geq$ 6000km	Insertion and Maintenance in an 'Aero-Brake' Like Environment
Access to altitudes between the Homopause and Exobase (1) and with measurements of the ionosphere	Periapsis below 170km and Near 150km	Density Corridor Control with an Unpredictable Density
Access to altitudes between the Homopause and Exobase (2)	Deep Dip campaigns with Periapsis Near 125km	Low Periapsis Target with an Unpredictable Density.
One earth year mission	Fuel to maintain periapsis in density corridor and to correct for perturbations from gravity and drag	Effects of density on fuel requirements and launch vehicle capability for the launch window

MISSION DESIGN OVERVIEW

MAVEN will launch in November 2013 and enter orbit around Mars in September 2014 after a ten-month cruise phase. The mission orbit will be elliptical, allowing measurements to be made at all altitudes throughout the upper atmosphere, at all local times with respect to the Sun, and at most latitudes. The primary mission will last one Earth year, providing sufficient time to make the key measurements to address the science objectives. Nominal science is conducted in a 4.5 hour period, 75 degree inclined orbit, with a ~150 kilometer periapsis altitude. MAVEN will perform five "deep dip" campaigns (5 days each) that will temporarily drop its periapsis altitude from 150 kilometers to ~125 kilometers. The periapsis is maintained relative to a density corridor rather than an altitude since the areodetic altitude varies due to the orbital eccentricity and the oblateness of Mars. For MAVEN, the argument of periapsis rotates at a rate of -0.808 deg per day and the Nodal rate is -0.629 deg per day, permitting science collection over a wide range of periapsis locations.

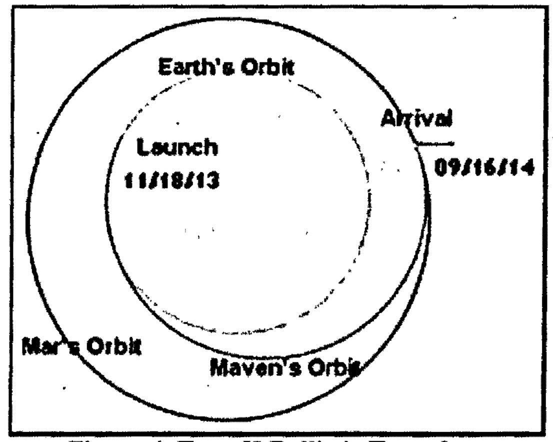


Figure 4. Type II Ballistic Transfer

Launch Window Analysis

MAVEN will launch from Cape Canaveral Air Force Station (CCAS) during a 20-day launch period opening November 18, 2013 on an EELV. The worst-case combination of injection energy and launch declination results in an allowable launch mass of 2720 kg, allowing a margin for the proposed 2550 kg wet mass. Upon arrival at Mars on September 16, 2014 (September 24, for a Dec 7, 2013 launch window close), MAVEN will insert into a capture orbit with a 35 hours period. Figure 4 shows the transfer trajectory and the dates of launch and arrival at Mars. 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, they can become the driver for the mission design and propulsion system selection. MAVEN was originally set for a launch in 2011, but was moved to 2013. This change resulted 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 ~ 200 m/s. This means that the current spacecraft design requires more fuel for the orbit insertion than the previous launch period and therefore a modified fuel tank is required. The geometry of approach is a northern approach which has DSN visibility over the launch period. Figure 5, shows contours of the C3 and V-Infinity for the desired launch period. One can see that the C3 over the launch departure dates are relative flat and decrease over the period by 2.6 km^2/s^2 . The V-Infinity 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 MOI Δv determined from V-infinity determines the close of the launch period. The launch declination remains under 28 degrees over the entire period and thus does not pose a concern for reduced mass capability. Table 2 provides launch period information for the MAVEN mission.

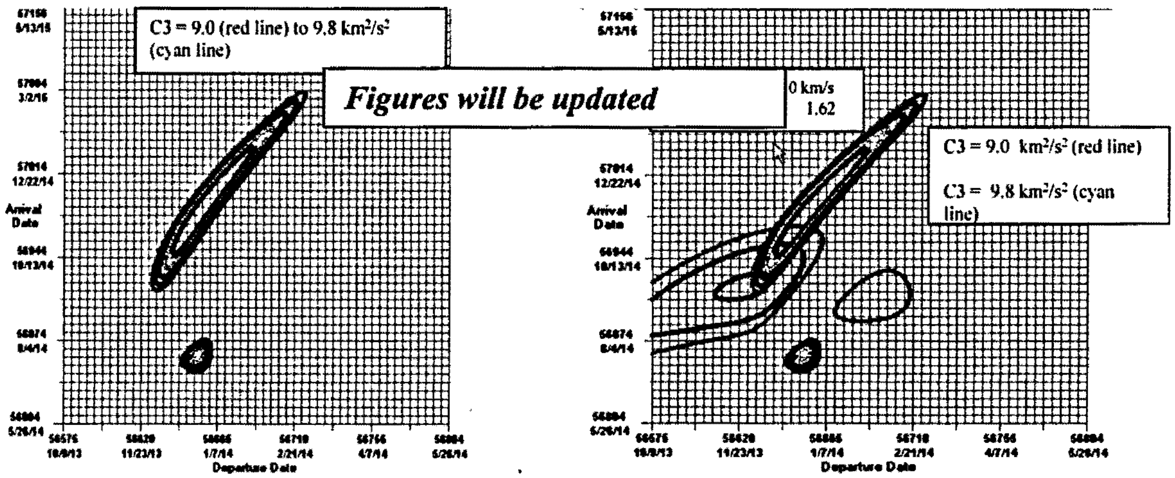


Figure 5. C3 and V-Infinity Contour Plots

Table 2: Launch Period Parameters

Launch Period	*Open*	*Mid*	*Close*
C3 (km^2/s^2)	12.07	10.30	9.40
Declination (deg)	13.38	18.84	26.93
Launch Capability (kg)	2720	2820	2875
MAVEN Launch Mass	2550	2550	2550
Arrival date	9/16/2014	9/20/2014	9/24/2014
Arrival V-Infinity	3.17	3.15	3.17

Cruise Phase

A simple, ballistic cruise phase as shown in Figure 4 prepares MAVEN for Mars arrival. The baseline transfer design is a Type II ballistic transfer to Mars (302 days) with two phases as shown in Figure 6. These two phases, inner and outer cruise, are used to calibrate engineering subsystems and instruments. There are four scheduled maneuvers during the transfer. These maneuvers are included from major lessons learned from previous NASA Mars missions. The first Trajectory Correction Maneuver (TCM-1) is executed as rehearsal for Mars Orbit Insertion (MOI) and to adjust the transfer trajectory due to planetary protection requirements. Planetary protection requires that the aim point of the targeted B-plane (periapsis) is located well away from Mars. This bias needs to be taken out and therefore performs double duty as the correction maneuver and a rehearsal using MOI designs. The use of Delta Differential One-Way Range (Delta-DOR) is also planned for precise navigation and for early characterization of non-gravitational forces. All payload activity ceases at MOI-60 days for final Mars approach.

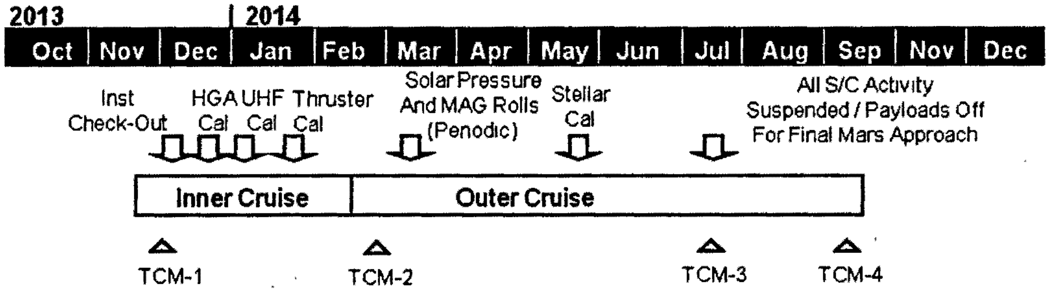


Figure 6. Transfer Phase Dates and Maneuver Operations

Mission Orbit Capture

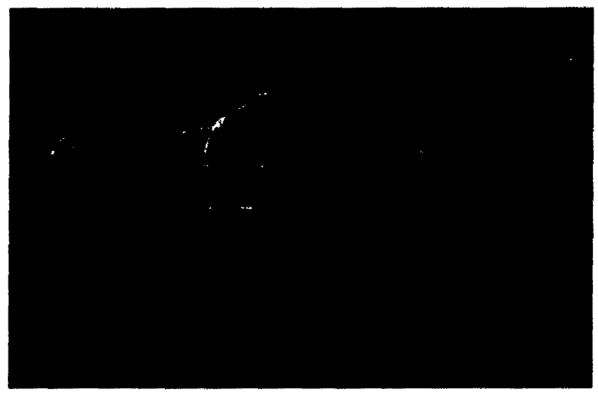


Figure 7. Northern Hemisphere Mars Orbit Insertion and the Capture Orbit

MAVEN performs an all-propulsive capture maneuver with a nominal thrust of 1321N, imparting a Δv of 1215 m/sec over 30 minutes to achieve a 35-hr orbit at 75° inclination with a post-capture periapsis altitude of 550 km. Subsequent maneuvers will reduce the period to a 4.5-hr orbit with periapsis near 150 km. A northern approach with a 5:45 pm local arrival time shown in Figure 7 provides Earth visibility during the entire insertion burn. The periapsis target for the incoming trajectory is 680 km, which will decrease to 550 km over the finite maneuver duration. MAVEN arrives on September 16, 2014,at a Local Solar Time of 5:45pm (September 24, 2014 for the window close). The northern approach offers a view of entire burn and there is no Earth occultation or solar eclipse. The MOI burn terminates on accumulated Δv. There is also a TCM-5a at MOI-24 hours and a TCM 5b at MOI-6 hours as contingency for Periapsis raises. These maneuvers are pre-built and tested during integration and test. A menu of maneuvers is resident on MAVEN at ~ MOI-3 Days.

MOI Restart Capability

As another challenge in this mission, it was determined that the possibility of engine shutdown during the MOI should also be considered. In order to alleviate most of this risk, the MOI will be started 2 minutes earlier than the nominal plan. MOI is designed such that no single fault will prevent the successful execution of the insertion burn.[7] Missions prior to MRO accepted risk of reboot, engine failure, IMU failure, etc, would end the mission. MAVEN advances the ignition point by 2 minutes (cost of 9.4 m/s) to achieve single fault tolerance. Advancing the burn allows a 14 minute outage in burn while still capturing into the 35 hour orbit. Maximum recovery from a spacecraft fault is 12.5 minutes. The MOI sequence is loaded at MOI-3 days and requires no further intervention from the ground. For any problems prior to the burn the MOI sequence is restarted autonomously; for problems during the burn, the burn is terminated, the issue resolved, attitude reacquired, and the burn restarted and completed autonomously. For problems after the burn, the issue is resolved autonomously and MAVEN remains in safe mode. Figure 8 shows how the orbital period and periapsis altitude are affected by an interruption. In the figure there are two lines each for captured period and captured periapsis. For example, if the time of interruption is at 10 minutes into the maneuver and the restart is 14 minutes later, the captured orbit period will be slightly over 100 hours, whereas without this plan the captured period would be nearly 350 hours. Similarly for the periapsis altitude, the captured altitude will be 490km versus 575km. The early MOI start takes advantage of restarts being more centered on periapsis and therefore more efficient than a restart using a nominal MOI start time.

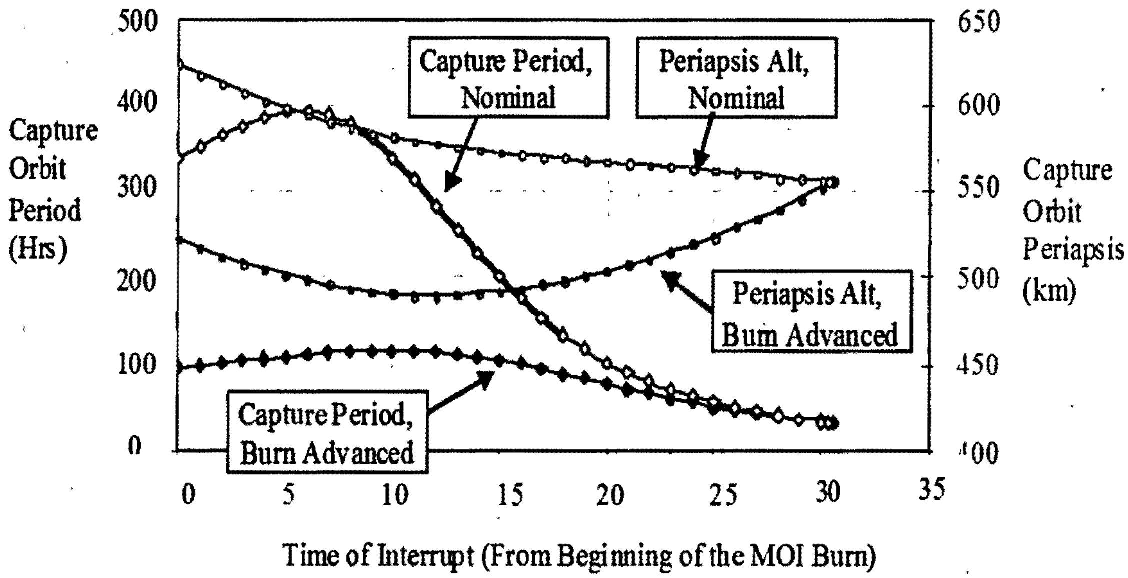


Figure 8. Fault Recovery Effects on Capture Orbit for a 14 Minute Interruption Occurring Anytime During Maneuver (Data Provided Courtesy LM, Denver)

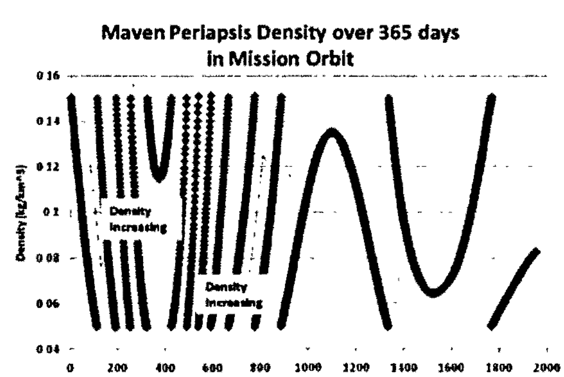
Mission Orbit Maintenance and Requirements

The MAVEN periapsis altitude is required to be maintained within a nominal density corridor between 0.05kg^2/km^3 to 0.15 kg^2/km^3 necessitating periodic trim maneuvers that have been modeled and accounted for in the ΔV budget. The change in the periapsis altitude is not due to the atmospheric drag but in fact due to the gravitational potential of Mars. The acceleration from the J3 potential term will cause periapsis to increase when the location of periapsis is in the northern hemisphere and decrease when the periapsis location is in the southern hemisphere. While this increase and decrease is sinusoidal and the amplitude predictable at roughly 15 km, the magnitude of the periapsis change will place MAVEN outside the allowed density corridor, thereby requiring maintenance via maneuvering at apoapais to adjust periapsis altitude.

In addition to this standard orbit profile, MAVEN will execute five "deep dip" campaigns, each with a 5-day duration (approximately 20 orbits), with periapsis at an atmospheric mass density corridor of 2 kg/km^3 (~125 km) to 3.5 kg/km^3. This low-risk strategy to collect highly desirable science capitalizes on experience gained on previous aerobraking missions such as MRO that were flown at considerably higher mass densities. Upon mission completion, MAVEN's periapsis is planned to be raised to approximately 250 km in order to provide against orbital decay resulting in a lifetime greater than 100 years.

Periapsis Maintenance

An analysis of the ΔV required to maintain the periapsis density corridor shows



that the maintenance maneuvers must occur at approximately monthly intervals. Figure 9 shows a sample maintenance profile for nominal mission maintenance of one year. One can see that the periapsis density corridor is maintained, and that the density profile is an inverse of the altitude profile since the lower densities are at the higher altitudes. As the periapsis increases or decreases, it will cross the density boundary and will need to be moved to the opposite density level depending on which direction the periapsis is changing. At beginning of life, the periapsis is naturally increasing so the density is decreasing and MAVEN will cross the upper density boundary. The maintenance maneuver will then lower periapsis altitude back to the higher density of 0.15 kg^2/km^3 and the process is repeated. Later in the mission the opposite effect occurs and density will increase since the natural change in periapsis will be decreasing and maneuver will raise periapsis.

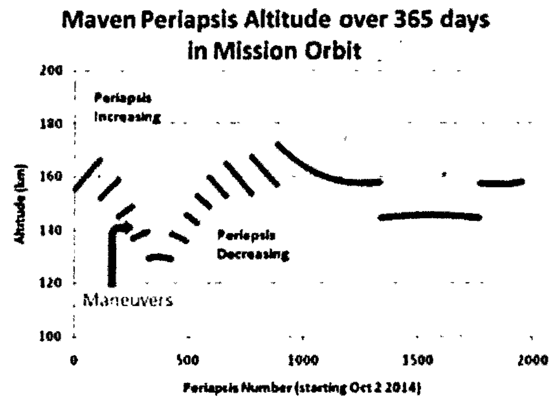


Figure 9. Periapsis Altitude (km) and Density (kg/km3) Arcs during Maneuvers Maintenance

While the Δv to move between the density levels is the roughly the same, the frequency of the maneuvers will change as a function of atmospheric conditions. The ΔVs used in the fuel budget dependent upon several input parameters including the Solar Flux F10.7cm prediction, use of mean or 2-sigma solar flux values, dust storms which can cause a factor of four increase in density, and the actual periapsis altitude due to eccentricity. Figure 9 shows that the altitude is increasing at the mission beginning of life (BOL) since the insertion argument of periapsis is at 135 degrees and is in the Northern hemisphere with an argument of periapsis rate of -0.808 degrees per day, meaning that the periapsis location is moving towards the northern latitudes. After approximately 120 days, the argument of periapsis has rotated to near the equator and is moving towards the southern hemisphere.

The Δv budget for the density corridor maintenance can be seen in Figure 9 which uses the spacecraft configuration and fuel mass based on the Concept Specification Report (CSR).[7] The simulation uses a MarsGram-2000 atmospheric model, a 5x5 gravity potential model, and all third-body perturbations including solar radiation pressure. This figure shows the cumulative Δv as well as the Δv required for the Deep Dip campaigns, which are discussed in the next section. The density value spikes during the deep dip campaigns are also shown. The total Δv required for maintenance alone is ~21 m/s and the Δv for the five Deep Dip campaign is ~ 49 m/s for a total mission orbit maintenance Δv of 70 m/s.

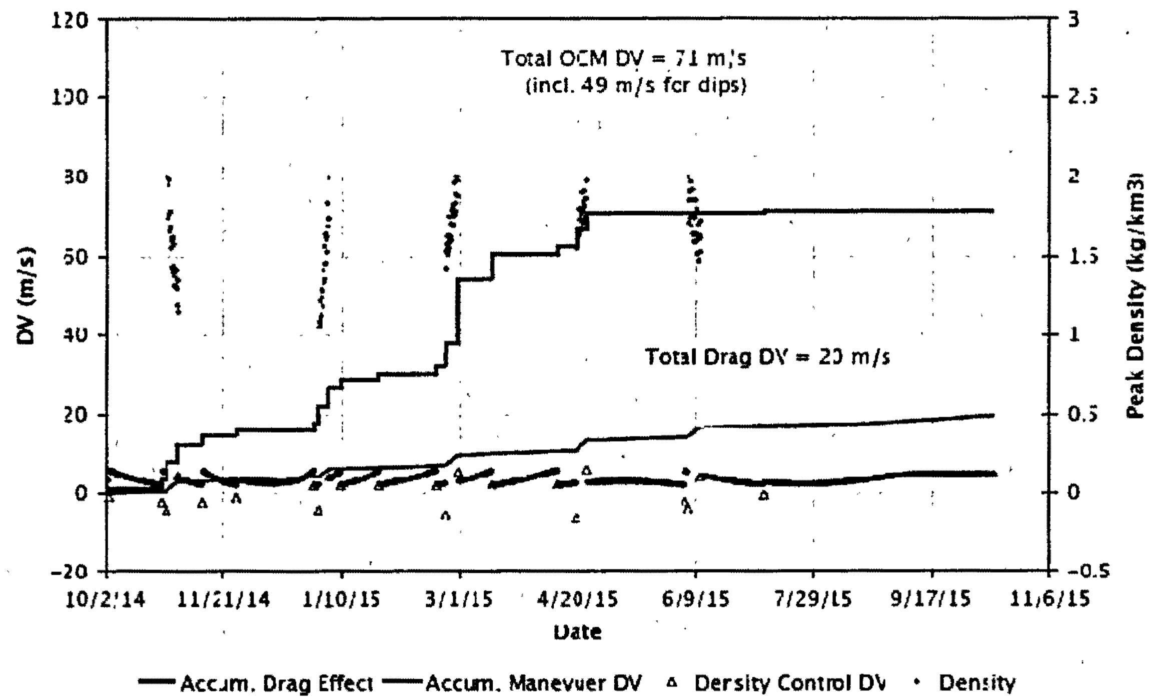


Figure 9. MAVEN Δv and Density over the Mission Life

Periapsis Timing Estimation

To assist in the determination of the location of periapsis and to meet an onboard 20 sec accuracy requirement, a Periapsis Timing Estimator (PTE) algorithm will be used onboard to adjust the ephemeris data, which is uploaded twice weekly. The PTE is used to compute the center of the periapsis passage. The 20 sec along track requirement for onboard timing is traced to the NGIMS instrument. With latency between the epoch of the navigation solution and the time it is used onboard, the PTE is used to ensure that onboard function using the ephemeris data have the most accurate time estimate for the periapsis. The PTE will use the accelerometer, subsystems such as reaction wheels and gyros, and the NGIMS instrument

Deep Dip Mission Design

More than any other segment of the mission design, the most significant challenge in this mission is the Deep Dip campaign. During these five campaigns, which last a week each over the one-year mission, the periapsis will be lowered to a density corridor of at least 2.0 kg/km^3. While this density is not near the aerobraking density of 50kg/km^3, it poses a significant challenge for both science data collection as well as spacecraft design and subsystem functionality. The Deep Dips are used by the NGIMS instrument and will require that all other instrument to be in a safe mode. It is critical during these deep dips to permit the periapsis density to be "walked in" over several orbits to ensure that the correct corridor can be met, given the unpredictability of the atmosphere. The duration of the deep dip campaigns cover approximately 37 orbits so the concept of a walk-in does not significantly reduce the science collection goals. During this phase, significant changes in the atmosphere (estimated to be a factor of four increase in density) can be caused by dust storms and solar flux changes. With this in mind we will walk into a final periapsis and tolerate the density conditions in terms of variability over the 5 day campaign. To ensure that MAVEN will survive both in orbit and subsystem design, MAVEN design will have a margin against the Deep Dip density. The nominal 0.008 W/cm^2 at 2kg/km^{3}is mitigated by a design requirement for S/C and instruments of 0.032 W/cm^2, this is a 400% margin for development uncertainties, atmospheric variability and dust storms and considered less than 0.04-0.07 W/cm^2 solar heat flux at Mars. The instruments sensitive to higher densities will be sequenced-off in advance of periapsis, approximately 5 minutes prior to critical pressure or ~550 km. The spacecraft will swap-sides and still safe instruments prior to critical pressure. In addition to the build in margin, an automated maneuver sequence will reside in memory to increase the periapsis to a safe altitude from which any spacecraft anomalies (if any) can be resolved. As shown in Figure 9, the change to the density profile is large and the Δv to accomplish this is nearly twice that of the nominal density corridor maintenance at 52 m/s to 24 m/s.

The Deep Dips will occur at pre-specified times over the course of the mission, at which a sampling of the lower atmosphere at different sub-solar locations (Mean local times) and different latitudes is desired. The dates for these Deep Dips are still under considerations at this time. It is anticipated that the first two campaigns will be operationally intensive as unique data is collected. Figure 9 shows that variation in density over the deep dips. Recent discussions with the science community have given rise to the possible use of a density corridor as used in the nominal mission orbit. This corridor is proposed to be 2.0 kg/km^3 to 3.5 kg/km^3. With the availability of performing periapsis adjustment only once every 4.5 hours and the possibility of the spacecraft being occulted, care must be taken to ensure that the periapsis does not drop below the spacecraft safety net of approximately 9 kg/km^3.

Collision Avoidance

Collision avoidance with other Mars orbiting spacecraft and both Phobos and Deimos must be accounted for in the overall design and in the Δv budget.[7] While the chance of a collision with other spacecraft may be remote, the MAVEN orbit does pass though all the orbits of the other Mars spacecraft with its low periapsis altitude of ~150km. Also, with a 4.5 hr period, the apoapsis is at a radial distance of 9610 km as compared to the sma of Phobos of 9000 km. With an argument of periapsis rate of -/808 deg per day, most of the mission life apoapsis will be far away from Phobos. In all cases the collision avoidance maneuvers are planned by comparing the spacecraft's ephemeris at relative nodal crossings. The avoidance is then applied as a small period change to the MAVEN orbit.

ΔV budget

The Δv budget to fly this mission is shown in Table 3. This budget includes all the deterministic Δv for planetary protection as well as statistical correction maneuvers for attaining the correct Mars insertion state. The budget is a '99%' Δv budget with a 50 m/s margin. There is also a margin on the propulsion system that includes a possibility of adding 127 kg to top off the tank. The current best estimate for the mass and mass margin is 2250kg which 1510.1 kg is fuel mass allocation.

Table 3: Mission ΔV Budget

Maneuver Description	Δv (m/s)	ISP (sec)	Fuel (kg)	Cumulative Total (kg)
TCM#1	20	237.5	21.8	21.8
TCM#2-5	10	237.7	10.8	32.6
MOI	1215	237.7	1020.6	1053.2
MOI Restart	10	237.3	6.0	1059.2
Periapsis Lowering	17	238.1	10.8	1070
Period Reduction to 4.5 hrs	544	237.3	306.9	1376.9
Orbit Maintenance	25.3	237.3	11.9	1388.8
Deep Dips	52	237.4	24.9	1413.7
Collision Avoidance	5	237.2	2.5	1416.2
EOM Orbit	16	237.2	7.4	1423.6
Δv Margin	50	237.1	23.0	1446.6
ACS (rotational)	66	180-174	47.3	1493.9
Ullage and errors	-	-	16.2	1510.1
TOTALS	-	-	-	**1510.1**

Nominal Mission Science Coverage

To meet the primary science orbit requirements to provide access to all latitude and solar times, it was necessary to design the mission so that the nodal and argument of periapsis rates permitted a rapid change in the periapsis location over the one-year mission duration. Given the requirements of apoapsis greater than 6000km, density corridors, and the 75 degree inclination, one finds that the nodal and argument of periapsis rates are also fixed by the planetary insertion conditions and orbital eccentricity. Fortunately, these rates do permit us to meet the latitude and solar time requirements. Shown in Figure 10 are the sub-solar (apparent sun) latitudes and longitudes at periapsis over the one-year mission. Included in this plot are the red highlighted areas that represent deep dip locations that are distributed over the mission. Figure 11 shows a 3-D view of the parameters that are computed to meet this requirement.

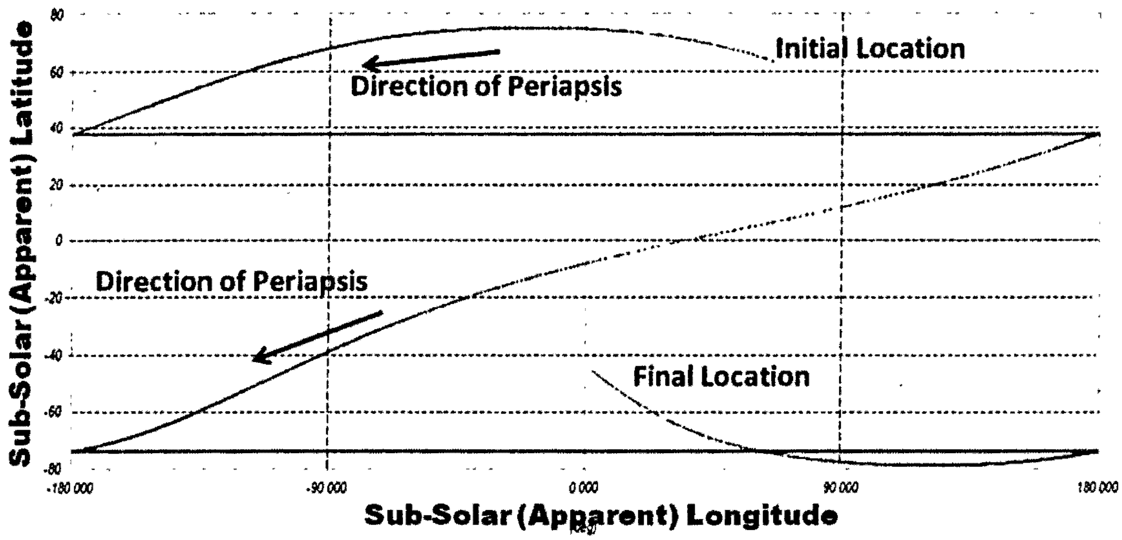


Figure 10. Solar Latitude and Longitude of Periapsis Location

Figure 11. 3-D View of Sub-Solar Periapsis Location

End Of Mission Options

The end of mission is nominally set to raise the periapsis altitude to 250 km so that the lifetime is greater than 50 years. This is a simple maneuver at apoapsis to raise periapsis in a single maneuver. Alternate scenarios have been investigated to see if MAVEN could continue its primary science for an additional time period if enough fuel were available. Of course the fuel available is dependent on how much is used for statistical maneuvers during the transfer, any adjustment to the periapsis density control design, and changes in the Deep Dip control. MAVEN can also perform as a relay spacecraft for other missions and can support this option in any orbit. Three possible end of mission options were analyzed, the continuation of the prime density corridor; an alternate corridor with maintenance maneuvers; and an uncontrolled option whereby the periapsis would meet science requirements over a portion of the time for a few years before a periapsis raise to the 250 km baseline. The Δv required for the first two options are similar to the prime mission maintenance, while the uncontrolled option which at first seems reasonable in that no translational maneuvers are required was prohibitive due to the fuel required for attitude control.

SUMMARY

The MAVEN mission design satisfies all the scientific challenges while providing both margins and spacecraft safety. The 20-day launch window can be met with margin and the fuel required for the transfer is reasonable and typical of a Mars mission. The insertion targets can be achieved without concern, and there are plans and algorithms in place during the critical Mars orbit insertion event to mitigate risk from an all-propulsive insertion strategy. The orbit requirements of an apoapsis greater than 6000 km while maintaining a low periapsis near 150km to meet a density corridor which is under the caprice of a highly variable atmosphere has been shown to be achievable. The low periapsis passages to meet science goals for both the nominal mission and the Deep Dip campaigns are under analysis and seem attainable as well. The baseline mission design plan has been completed, and the MAVEN project is readying for the preliminary design review.

CONCLUSIONS

The Goddard Spaceflight Center and the MAVEN team are looking forward to support of this next Mars mission. The mission design must meet many challenges, but the MAVEN team has shown that all the science requirements that drive the mission design can be met and that the mission design is viable and implementable.

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