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MAVEN NAVIGATION OVERVIEW

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The Mars Atmosphere and Volatile Evolution mission (Maven) is the first mission devoted primarily to the study of the Martian atmosphere. The Maven orbiter launched on November 18, 2013, entered Mars orbit on September 22, 2014, and continues to acquire measurements of Mars' upper atmosphere in an effort to understand the loss of Martian volatiles to space. The navigation team is responsible for estimating and predicting Maven's position and velocity, and designing and reconstructing propulsive maneuvers. After Mars orbit insertion, the team faced additional challenges unique to Maven's orbit and tracking data schedule, including the determination of the atmospheric density at each periapsis, which is necessary to keep the spacecraft within a predefined density corridor. This paper briefly describes the Maven mission and overviews the operations of the Maven navigation team from launch through the nominal science phase.

INTRODUCTION

In 2008, NASA selected the Mars Atmosphere and Volatile Evolution mission (Maven) as the second and final mission of the Mars Scout Program.[1] The Maven mission, managed by NASA's Goddard Space Flight Center, studies the composition, structure, and dynamics of Mars' upper atmosphere; it is the first mission dedicated to Martian aeronomy. To carry out this investigation, the Maven spacecraft orbits Mars for at least one Earth year and carries a suite of instruments for collecting remote and in-situ measurements. To facilitate acquisition of the desired scientific data, Maven's navigation team at NASA's Jet Propulsion Laboratory (JPL) controls, reconstructs, and predicts the spacecraft's trajectory.

Maven left Earth on Nov. 18, 2013 bound for Mars. Along the way, the spacecraft performed two trajectory correction maneuvers (TCMs) and arrived for Mars orbit insertion (MOI) on Sep. 22, 2014 (UTC). After a multi-week transition phase with five maneuvers to reduce the orbital period and lower the periapsis altitude, the spacecraft achieved an orbit with a period of 4.6 hours, an equatorial inclination of 74 deg, an eccentricity of 0.47, and a periapsis altitude of about 180 km, to give an atmospheric density at periapsis near 0.05 kg/km^3. The nominal science phase lasted one year and included four one-week "deep-dip" campaigns where the periapsis altitude was lowered to achieve an atmospheric density between 2.0 and 3.5 kg/km^3. Maven's science phase will extend past one Earth year, and, eventually, Maven will act primarily as a communications relay for spacecraft arriving at Mars and those on the surface.

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With its distinct orbit and suite of instruments, Maven can obtain unique data on Mars' atmosphere in unprecedented detail. Maven's low periapsis altitude and the fact that the periapsis latitude naturally oscillates between +75 and -75 deg allows Maven to study the Martian upper atmosphere at various times of day, across a range of latitudes, at different seasons in the Martian year, and throughout a portion of the solar cycle. The orbit was also chosen such that its periapsis path crosses noon local solar time with subsolar latitude near 0 deg. Characterization of the Martian thermosphere ($\sim$100–250 km), ionosphere ($\sim$100–400 km), and exosphere ($\sim$300+ km) is necessary to estimate atmospheric escape from Mars, and knowledge of the current escape rates of volatiles informs the estimation of the total loss through Mars' history.[2] Previously, the mass density of Mars' thermosphere was measured by onboard accelerometers on Mars Global Surveyor (MGS), Odyssey, and Mars Reconnaissance Orbiter (MRO). The only in-situ ionospheric measurements were conducted during the descent of the Viking 1 and 2 landers. Maven will characterize the full thermosphere-ionosphere-exosphere system, and the implications of this characterization on the evolution of water on Mars is of particular interest because no evidence yet exists for life without it.

This paper overviews the Maven mission and the work of the navigation team that enabled Maven to reach its intended destination and remain in the desired Mars orbit during science operations. First, a brief description of the spacecraft and its instruments is presented. The following section presents the responsibilities of the navigation team. Next, a chronological outline of the mission is presented, including launch, cruise, transition, and nominal science phases. Since Maven's interplanetary cruise phase executed almost entirely nominally and was similar to previous missions that have been well documented (see, for example, Refs. [3–6]), many details are omitted and more focus is placed on Maven's distinct orbit and nominal science-phase operations at Mars.

SPACECRAFT

Built by Lockheed Martin, Maven is a three-axis stabilized spacecraft 11.4 m wide with fixed solar panels, a fixed two-meter high-gain antenna (HGA), and two low-gain antennas (LGA) (Figure 1). Maven uses a monopropellant propulsion system with six 170 N main thrusters, six 22 N TCM thrusters, and eight one Newton attitude control system (ACS) thrusters. The solar panel segments have an active surface area of about 12 m^2, and the outer panels are canted 20 deg for stability during passes through the Martian atmosphere. The fixed HGA is used for telecommunications during the late cruise phase (90 days after launch through MOI) and twice weekly during the nominal science phase for commanding, and telemetry and data download. An LGA is used for telecommunications during the early cruise phase (within 90 days of launch), critical events, and in orbit at Mars.

Maven's attitude is maintained with four 100 Nms reaction wheels. The asymmetric spacecraft experiences a net torque due primarily to solar radiation pressure, gravity gradient, and aerodynamic forces. The accumulated angular momentum is periodically unloaded through thruster firings called angular momentum desaturation events (AMDs or "desats"). The desats are carried out by firing ACS thrusters in pairs such that a torque is imposed on the spacecraft in the correct orientation to force the wheels to spin down. In theory, the ACS thrusters would be perfectly aligned and produce equal thrust, and thus produce a torque with no resultant linear acceleration. This is not feasible in practice, however, and each desat produces a small translational Δv. Maven conducted desats approximately once per week during interplanetary cruise and once per orbit during the nominal science phase. The ACS thrusters were balanced well enough that the average desat magnitude during cruise was estimated to be 0.47 mm/s. These desats were the most significant trajectory perturbations during cruise.

Maven carries eight science instruments built by the University of Colorado at Boulder, the University of California at Berkeley, and NASA's Goddard Space Flight Center.[7] The Neutral Gas and Ion Mass Spectrometer (NGIMS) measures the composition of gases and thermal ions in Mars' upper atmosphere, including density profiles of CO_2, O_2, and N_2.[2] The Imaging Ultraviolet Spectrometer (IUVS) performs wide-field remote sensing at apoapsis of the science orbit to measure global characteristics of the upper atmosphere and ionosphere. Maven also carries the Particles & Fields "package", which includes the following six instruments: Solar Wind Electron Analyzer (SWEA), Solar Wind Ion Analyzer (SWIA), Suprathermal and Thermal Ion Composition instrument (STATIC), Solar Energetic Particle instrument (SEP), Langmuir Probe

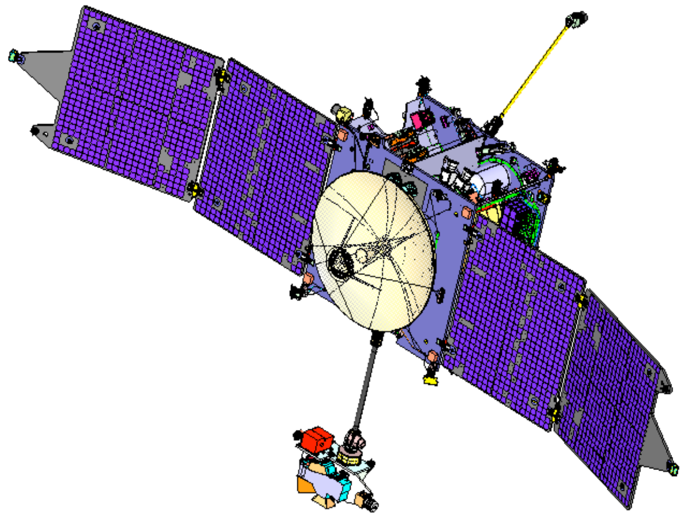


Figure 1. Maven spacecraft shown with deployed articulated payload platform, as in Mars orbit. Two seven-meter booms for the Langmuir Probe & Waves instruments are not shown. (Image courtesy of Lockheed Martin.)

& Waves instrument (LPW), and the Magnetometer (MAG). The primary instruments performing in-situ measurements during the periapsis phase of Maven's science orbit are NGIMS, LPW, and STATIC. In addition to the eight science instruments, Maven carries the JPL-provided Electra ultra-high frequency (UHF) relay radio transmitter and receiver for communication with surface assets.[8] The IUVS, NGIMS, and STATIC instruments are located on the articulated payload platform (APP) which is the only articulating part of the spacecraft. The APP was stowed during cruise and deployed in Mars orbit (see Figure 1), but its effects on Maven's dynamics are ignored in navigation analyses.

NAVIGATION SYSTEM

JPL performs measurement acquisition, orbit determination (OD), and flight path control for Maven. Radiometric tracking data measurements are acquired at the Deep Space Network's (DSN) complexes in Goldstone, California; Canberra, Australia; and Madrid, Spain. The navigation team (Navigation) at JPL performs: 1) OD to determine the past, present, and future position and velocity of the spacecraft, reconstruct propulsive maneuvers, and deliver spacecraft ephemerides and associated products to the DSN and the spacecraft team, and 2) maneuver design and analysis to control the spacecraft's trajectory. The majority of the navigation team's operations are performed with JPL's Mission analysis, Operations, and Navigation Toolkit Environment (Monte),[9] which is the software used for navigation on all new JPL flight missions. For OD analyses, the operations performed with Monte include integrating the spacecraft's trajectory, computing the differences between the observed and computed values of tracking data, computing the partial derivatives of the tracking data with respect to the estimated parameters, and filtering the data with a least-squares process.

An accurate dynamic model is crucial for an accurate orbit solution, and the Monte software suite provides a framework for high-precision simulations. The model used here includes gravity from the sun, the planets, and Pluto. Planetary moon systems are grouped with their central body at their mutual barycenter. Near the Earth, during the early cruise phase, the Earth and moon were considered separately and were modeled with 8×8 spherical harmonic gravity fields. When Maven is in Mars orbit, Mars, Phobos, and Deimos are considered independent gravitating bodies, and Mars is modeled with the MRO110c 110×110 spherical harmonic field. Non-gravitational forces include atmospheric drag, propulsive maneuvers, solar radiation pressure and thermal re-radiation, AMD thruster firings, and spacecraft outgassing. The Mars atmosphere is modeled with the 2005 Mars Global Reference Atmospheric Model (Mars-GRAM).[10] Planetary states are obtained from JPL's DE430 ephemeris, and states of bodies in the Martian system from the MAR097 ephemeris. In calculating DSN station positions, solid Earth tides, pole orientation, and plate motion are included.

For navigation during interplanetary cruise, Maven used three tracking data types: two-way coherent Doppler, two-way coherent range, and delta differential one-way range (ΔDOR). Range and Doppler provide line-of-sight range and range-rate information, and ΔDOR provides plane-of-sky angular position information. Because propagation through the Earth's troposphere and ionosphere significantly alters radiometric signals, media calibrations provided by the DSN are applied to account for these effects when the data are used for navigation purposes. The tracking data schedule from launch through the nominal science phase is shown in Table 1. All three data types were utilized during cruise; only Doppler is used in Maven's science phase. An eight-hour pass listed on the schedule does not imply that eight hours of tracking data will be received, because the eight hours includes the time required for spacecraft lockup and light-time delay. A reduced amount of data was usually not significant during the mostly quiescent cruise phase, but it is of great concern during the science phase where the orbit is perturbed by the Martian atmosphere, and where only about one periapsis per day falls within a tracking data pass.

Table 1. Tracking data schedule

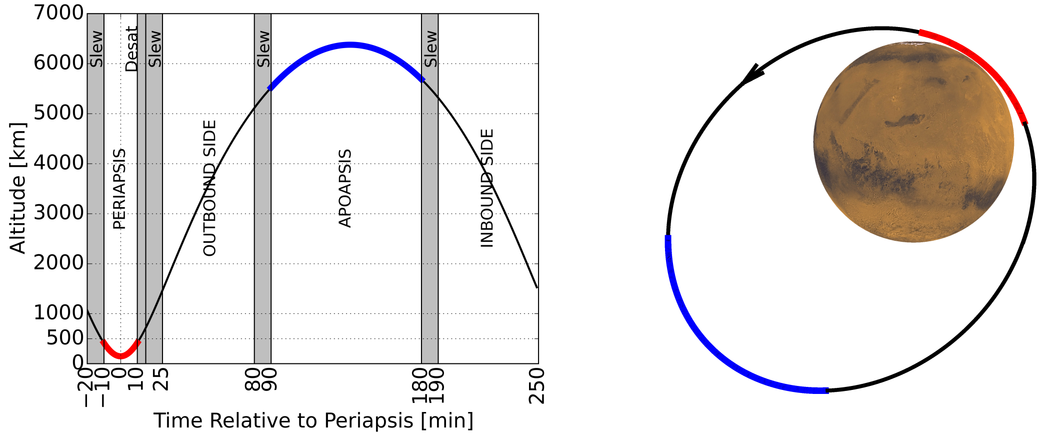
Mission Phase	Begin	End	Event	Range	Doppler	ΔDOR
Cruise	L[a]	L + 27 day		Continuous	Continuous	None
	L + 27 day	L + 90		3×8 hr/wk	3×8 hr/wk	None
	L + 90	M[b] - 60		3×8 hr/wk	3×8 hr/wk	1/wk
	L + 98.5	L + 101.5	TCM-2	Continuous	Continuous	1/wk
	M - 60	M - 11		8 hr/dy	8 hr/dy	2/wk
	M - 61.5	M - 58.5	TCM-3	Continuous	Continuous	2/wk
	M - 11	M		Continuous	Continuous	2/wk
Transition	M	M + 10		None	Continuous	None
	M + 10	M + 39		None	12 hr/dy	None
Science	M + 39			None	8 hr/dy	None
	DD[c] - 2	DD + 9	Deep Dip	None	Continuous	None

[a] Launch epoch.
[b] MOI epoch.
[c] Start of deep dip.

Weekly ΔDOR measurements were used 90 days after launch until MOI. Initially, three data points were recorded during each ΔDOR measurement session along both the Goldstone-Madrid and Goldstone-Canberra baselines. Due to Maven's relatively low pre-MOI declination, beginning in Aug. 2014, the Goldstone-Madrid baseline captured only two points per session. The initial 1σ value used for ΔDOR measurements was 0.06 ns; for the low-elevation measurements on the Goldstone-Madrid baseline, this value was increased to 0.1 ns in late August and rose to 0.15 ns before MOI (1 ns corresponds to an angular displacement of about 2×10^{-6} deg for the DSN).

Science-Phase Challenges

Though Maven's interplanetary cruise phase was similar to that of previous Mars missions, several aspects of Maven's mission in Mars orbit present challenges for the navigation team.[11] The orbit is unique for the primary phase of a Mars spacecraft, so experience from prior missions does not present a complete picture of the atmospheric conditions Maven experiences. This, coupled with the objective of maintaining a density corridor (as opposed to ephemeris targets), presents some unique challenges for navigation. The first challenge is that Maven's orbit at Mars must be maintained to collect science data while repeatedly passing through Mars' atmosphere. Maven's nominal orbital phase at Mars is similar in some respects to previous missions, but this similarity holds only when considering the aerobraking phases of the prior missions. In fact, Maven's nominal science orbit can be considered "light aerobraking", and, unlike previous missions, Maven must meet stringent navigation requirements during this phase to satisfy its scientific objectives. A second challenge for the team is meeting the science-phase navigation requirements with significantly less tracking



(a) Orbit phases with approximate event times

(b) Oblique view

Figure 2. Representative Maven science orbit

data than during the aerobraking phases of previous missions. Whereas Maven has approximately seven hours of tracking per day, MGS, Odyssey, and MRO had continuous tracking during aerobraking. Maven also receives less tracking data than MGS, Odyssey, and MRO received during their primary science phases. Third, to accommodate the preferred orientation of the onboard science instruments, Maven utilizes ten sets of two-orbit attitude profiles, with each profile representing four attitude segments. Slews between attitudes for a single example orbit are shown in Figure 2. The possibility of four different orientations during each orbit increases the complexity of accurately modeling the spacecraft dynamics, and, if data during spacecraft reorientations is deemed to be of poor quality, this further reduces the amount of valid tracking data. Fourth, with a nominal periapsis altitude near 150 km, Maven's orbit presents a challenge for accurately estimating the atmospheric density at periapsis, with an assumed 100% orbit to orbit variation. Finally, the compressed timeline for Maven's deep dips requires accelerated analyses by the navigation analysts.

During the cruise phase, the Maven navigation system was required to design MOI to place Maven in Mars orbit with a period of 35$\pm$5 hr, an inclination of 75$\pm$1.5 deg, and an altitude of 380$\pm$50 km at the first periapsis after MOI (all values are 3σ). During the post-MOI transition phase, the Maven navigation system was required to guide Maven to an elliptical nominal science orbit with a period of 4.5$\pm$0.11 hr, and an inclination of 75$\pm$1.875 deg. These requirements exist to place Maven in an orbit that allows Maven's suite of science instruments to obtain the desired measurements of Mars' atmosphere.

During the nominal science phase, the Maven navigation system is required to:

- Target a nominal periapsis density corridor of 0.05–0.15 kg/km^3, and a deep-dip corridor of 2.0–3.5 kg/km^3
- Predict the time of periapsis to less than 20 seconds for the first orbit after ephemeris upload
- Predict, for at least 9.5 days in the nominal science orbit and at least 2.8 days during deep-dip orbits, Maven's orbital elements to within the following 3σ accuracies:
  - Semi-major axis: $\pm$50 km
  - Eccentricity: $\pm$0.025
  - Inclination: $\pm$0.20 deg
  - Longitude of the ascending node: $\pm$0.04 deg
  - Argument of periapsis: $\pm$0.3 deg
- Reconstruct the position of the orbiter to within 3 km (3σ), excluding atmospheric blooming[§] events

[§] A temporary increase in atmospheric density.

- Be capable of performing orbit trim maneuvers (OTMs) as frequently as every 7 days, and as frequently as once per day during deep dips
- Maintain an orbit period of 4.5±0.11 hr

The requirements on the accuracy of the predicted trajectory are imposed to satisfy the pointing requirements of Maven's science instruments. In operations, the periapsis timing requirement implies that the predicted trajectory delivered by the navigation team must predict periapses within 20 sec over 1.7 days, because this is the elapsed time between the end of OD analyses and the first periapsis after the ephemeris upload.[12]

Since Maven's HGA is not gimbaled, the spacecraft must reorient itself for HGA communication with Earth, and, therefore, science observations are compromised during this interval. To minimize such periods, Maven communicates with Earth via its HGA only twice per week, downloading spacecraft telemetry and science data, and uploading a new ephemeris, spacecraft command sequences, etc. Since pre-launch studies showed that the navigation system could meet the periapsis timing requirement for only 2.3 days but not continuously from each HGA pass to the next,[12] Maven relies on its onboard Periapse Timing Estimator (PTE),[13] developed by Lockheed Martin. Once per week (initially twice per week, during each HGA pass), PTE is initialized by Navigation's predicted trajectory, and this keeps the timing error within 20 seconds. In its configuration during most of the nominal science phase, PTE achieves its estimate of the periapsis epoch by calculating the drag pass centroid time with reaction wheels and onboard accelerometers. Knowledge of the periapsis epoch is necessary for the timing of spacecraft events during each orbit.

Since HGA transmissions nominally occur each Tuesday and Friday, OD analyses are performed each Monday and Thursday to produce a predicted trajectory for upload to the spacecraft on the following day. In addition to the spacecraft ephemeris, the navigation team, in concert with the spacecraft team, science team, and project management, use reconstructed and predicted atmospheric density estimates to determine if an OTM is necessary to remain in the density corridor. The predicted trajectories are also used for science operations planning, and by the DSN for frequency predicts and antenna pointing. Reconstructed trajectories are delivered weekly, typically on Wednesday after receiving vehicle attitude information during the two previous HGA passes earlier in the week. The stringent requirements and atmospheric variability during deep-dip campaigns require reconstructed and predicted trajectories and associated products to be delivered daily. (During the cruise phase, an OD solution was delivered every ten days on average, except during the week after launch and the week before MOI, when solutions were delivered more frequently.)

Orbit Determination

In the cruise OD process, the navigation filter strategy involved estimating the initial spacecraft state, non-gravitational forces like solar radiation pressure, range biases, and the three components of each impulsive burn used to model each desat occurring during the OD trajectory arc (nominally once per week), though the ability to accurately estimate the plane-of-sky components of the desats was questionable. To model solar pressure, Maven was approximated as a series of flat plates with individual specular and diffuse coefficients. In general these coefficients were not estimated, but rather an overall scale factor on the solar pressure force. In the period shortly after separation when a spacecraft is heated by the sun and exposed for the first time to the vacuum of space, foreign materials trapped or frozen inside or outside the spacecraft can evaporate or sublime. These escaping gases induce an acceleration on the spacecraft, with the effect most pronounced immediately after separation and diminishing rapidly thereafter. For Maven, the navigation team modeled this phenomenon with a decaying exponential acceleration; and the effect became insignificant for OD analyses within two weeks of launch. Additionally, in the late cruise phase, media effects like troposphere and ionosphere signal delays; DSN station locations; the gravitational parameters of the Earth, moon, and Mars; the state of the Earth barycenter and Mars barycenter; and quasar positions were included as "consider" parameters to account for their expected accuracy, but were not estimated.

In the science OD process, the default filter strategy is to estimate the initial spacecraft state, a solar radiation pressure scale factor, three components of each desat (nominally occurring once per orbit), and a density scale factor whose value is updated once per orbit. Propulsive maneuvers are estimated as finite burns, or, in the case of short duration burns, as impulsive maneuvers. Since each desat occurs about 10 minutes after periapsis, near the region of significant atmospheric density, and since most desats have a magnitude less than 1 mm/s, the ability to accurately estimate these events is compromised. The baseline science-phase filter assumptions are summarized in Table 2.

The estimation of the density scale factor is crucial not only because the error in Maven's position is dominated by uncertainty in the atmosphere, but also because the navigation team's periapsis density estimates are used by Maven's science team in combination with other density estimates to measure the current state of the atmosphere. Furthermore, accurate density reconstructions are required to improve density predictions, and therefore improve maneuver decisions. Navigation has adopted the Mars-GRAM 2005 atmosphere model,[10] initially using Map Year 1 (MY1), and later with Map Year 0 (MY0). The density scale factor (to Mars-GRAM) is the only estimated atmospheric parameter, and it exhibits 3σ orbit-to-orbit uncertainties of 100%. These variations have some correlation with Maven's changing periapsis latitude and solar angle but are dominated by random noise.

A corrected density scale factor accounts for variation in net drag Δv; however, uncorrected variations in the shape of the drag curve can negatively impact navigation performance. In particular, meeting the reconstructed position uncertainty requirement of 3 km during deep dips is difficult, and it is postulated that unmodeled wave variations in the atmosphere are the cause. As an example, if actual peak density is biased relative to Mars-GRAM, a periapsis timing error will result, thereby degrading reconstructed accuracy. Unfortunately, Doppler provides observability of net Δv only. Navigation experimented with telemetry-derived observables (in particular accelerometer data) to estimate these higher-order variations,[14] but such techniques are not used operationally, except as a secondary source in decision making.

The other significant error source when estimating density is uncertainty in the product of the coefficient of drag and the drag area ($c_d A$). Since the drag force, which is observable, is proportional to the product of density and $c_d A$, the individual parameters are linearly dependent. Moreover, Maven's frequently changing attitude causes errors in $c_d A$ to vary orbit-to-orbit. To reduce the magnitude of this uncertainty, tabulated $c_d A$ values as a function of the body-fixed atmospheric velocity are used. These values are derived from pre-launch CFD analyses. This approximates surface shadowing better than the typical approach of modeling the spacecraft by a few major two-dimensional shape elements.

Maneuver Design

Maven's required orbit at Mars was achieved by designing and executing propulsive maneuvers, including cruise-phase TCMs, MOI, and several maneuvers in the post-MOI transition phase. During cruise, the navigation team performed OD to monitor Maven's trajectory to predict its post-MOI orbit, and, if necessary, this information was used to modify the TCM and MOI burns. The post-MOI transition maneuvers and corresponding OD were performed to both lower the periapsis and reduce the orbital period. These maneuvers were either fully designed, pre-designed, or selected from a fixed Δv "menu".

In the science phase, orbit trim maneuvers (OTMs) make up the bulk of all executed maneuvers, as these maneuver decisions are made weekly to maintain Maven's density corridor. This weekly frequency is required because the periapsis density in the reconstructed trajectories varies significantly due to the sometimes

Table 2. Science Phase Baseline Filter Assumptions

Error Source	Type	Apriori Uncertainty (1σ)	Units	Note
X-Band Two-way Doppler	Measurement	0.1	mm/s	
Epoch State Position	Estimated	100	km	Per axis
Epoch State Velocity	Estimated	0.1	km/s	Per axis
Solar Radiation Pressure Scale Factor	Estimated	10%	-	
Density Scale Factor	Estimated, Stochastic	$\frac{1}{2}\cdot$ Initial Value	-	Updated once per orbit
Angular Momentum Desaturations	Estimated	0.1	mm/s	Per axis
Orbit Trim Maneuvers	Estimated	$0.02 + 0.04 \cdot \Delta v/(3\sqrt{2})$	m/s	Pointing error
		$0.02 + 0.02 \cdot \Delta v/3$	m/s	Magnitude error

unpredictable nature of the Martian atmosphere and Maven's limited ability to observe it. Therefore, the OTMs are designed to target an average periapsis density within the desired corridor, not necessarily to stay within the corridor itself. To be able to design and execute OTMs quickly, and to reduce the chances of executing an incorrect maneuver, the maneuver execution options are simplified. OTMs are always performed at apoapsis in the velocity or anti-velocity direction, with a magnitude chosen from a fixed Δv menu. The menu ranges from 0 m/s to 0.6 m/s in increments of 0.2 m/s, and from 0.6 m/s to 6 m/s in increments of 0.3 m/s; no other values are permissible. During deep-dip campaigns, deep-dip maneuvers (DDMs) are utilized to enter, maintain, and exit the deep-dip density corridor. The drag forces and periapse density uncertainties increase dramatically at these lower altitudes, so DDM opportunities occur daily. DDMs are similarly chosen from the same Δv menu as the OTMs, but their decisions and executions are on a tighter time schedule.

Other considerations in Maven's maneuver design include correcting its orbital period and avoiding collisions with other Mars orbiters. Period correction maneuvers (PCMs), executed at periapsis, are required occasionally due to the accumulated effect of drag. Collision avoidance criteria typically do not dictate independent maneuvers and are instead taken into account when selecting weekly OTM choices.

Deep Dips

Maven performs week-long deep-dip campaigns to provide in-situ sampling of the Martian upper atmosphere at a periapsis density between 2.0 and 3.5 kg/km^3. Each deep dip ideally lasts eight days, including two days for up to three "walk-in" maneuvers to lower the periapsis altitude, five days of science measurements, and one day for "walk-out" maneuvers. Telecom coverage is continuous during deep dips; otherwise, there could be dangerously high densities encountered by the spacecraft.

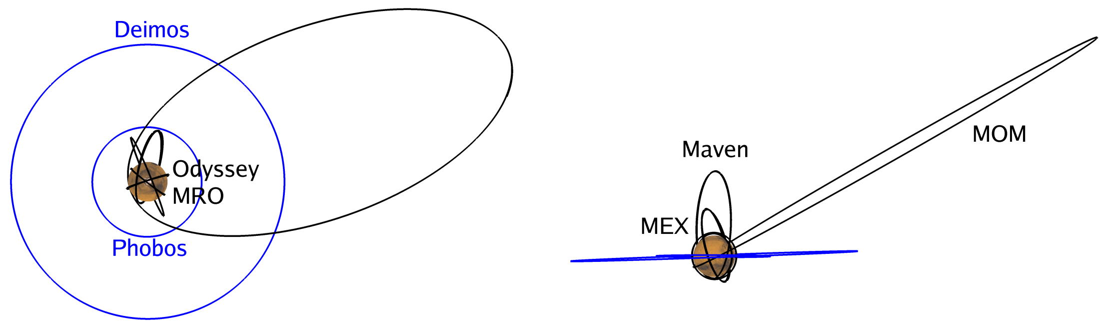
To maintain the deep-dip corridor, Navigation must perform OD analyses and design an OTM every day. A Navigation-generated ephemeris must be uploaded before the third periapsis after the last periapsis in the OD analysis to satisfy the PTE timing requirement. Since Navigation uses three post-OTM periapses to estimate density and design the next OTM, this means that the navigation team has five hours after the third periapsis of each day to complete OD analyses, design the OTM, and deliver the required products to the spacecraft team. Additionally, Navigation delivers daily reconstructed trajectories once the attitude history of the spacecraft has been downloaded.

Collision Avoidance

With five operational spacecraft and two natural satellites, the orbital space around Mars is becoming increasingly crowded (Figure 3). Though orders of magnitude less crowded than Earth, with correspondingly smaller probabilities of collisions, the potential consequences of a collision would be disastrous, making approach monitoring and collision avoidance (COLA) an operational task of great concern. COLA analyses for the Maven mission consider the Odyssey, MRO, Mars Express (MEX), and Mars Orbiter Mission (MOM) spacecraft, as well as the moon Phobos. Deimos' orbit is higher than the apoapsis of the Maven orbit, and the orbits of defunct spacecraft are too poorly known to perform any useful analysis.

Geometrically, a collision between two bodies would only be possible at the intersection of their orbital planes, locations referred to as the nodes.[¶] Potential COLA encounters are characterized by the difference in orbit radii at a node (the nodal range) and the time difference between the arrival of each spacecraft at that same node. This parameterization is advantageous because the orbit shapes are typically well known and slowly changing, while the phasing of the orbit can be highly variable, particularly for Maven. Thus, the parameterization distinguishes between (e.g.) a low-risk 50 km encounter with a 45 km nodal range, and a much riskier downtrack 50 km encounter. For Maven, uncertainty is dominated by drag-induced phasing errors, subject to $\sim$30% mean and $\sim$100% orbit-to-orbit uncertainties in the atmospheric density. When combined with a nominal drag model, the future period and timing uncertainty at a node can be computed, as well as the nodal range uncertainty and associated correlations. This allows a single "sigma-level" distance for an encounter to be calculated as a Mahalanobis distance. While current analyses assume that other bodies are much better known than Maven, it would be a straightforward extension to include uncertainties from

[¶]Excepting the pathological case of co-planar orbits, which was not an issue for Maven during its first Earth year of science operations.



(a) Polar view with near-circular orbits labeled (b) Equatorial view with eccentric orbits labeled

Figure 3. Active satellites of Mars

both bodies in this manner. Special care must be taken with Phobos, with its 14 km maximum radius, to ensure that the distances are measured to the outside of the sphere rather than the center of mass; Navigation currently uses a "keep-out" zone of 30 km for the nodal crossing distance and 15 sec for the orbit crossing timing.

High-risk potential COLA encounters are mitigated using period-altering maneuvers designed to shift the timing of the encounter in question. To simplify operations, Maven uses the existing corridor control OTM process to implement any required COLA mitigation, with the option to implement a maneuver twice a week, with each predicted trajectory delivery and scheduled uplink. Given long-term reference trajectories, multi-day "COLA seasons", when the nodes are close and collisions are possible, can be predicted well in advance. During these seasons, a detailed nodal analysis is performed with each predicted trajectory, and a maneuver is recommended to the project if necessary. If a mitigation maneuver is required, the decision to use apoapsis maneuvers means that the periapsis density targeting may be corrupted. Fortunately, given the timelines and timing uncertainties, COLA mitigation maneuvers are expected to be $\sim$1 m/s in magnitude, and it is likely that either an up or down OTM will be able to effectively mitigate the encounter, and one of the options will simultaneously maintain the corridor by taking the place of a future OTM. The reverse is also true. When selecting OTMs, an awareness of upcoming COLA encounters means that selections can be made that both maintain the corridor and reduce the likelihood of future COLA events.

Collision avoidance is a multi-mission process. Except in the case of Phobos, it should be possible for either body to make an orbit change to avoid an encounter. Furthermore, knowledge of other pre-planned activities is required to inform decisions, so every COLA season involves active communication between project teams. Due to its low periapsis altitude, the Maven prediction accuracy is much worse than the other spacecraft and Phobos; therefore, Maven navigation error analyses are the primary driver for any COLA decision. With its weekly maneuver opportunities, Maven is also generally more capable of performing an action. Therefore, to simplify possible multi-mission decision processes, Maven has taken on the responsibility of performing any necessary COLA maneuvers during its primary science phase, provided it is operating nominally. However, conditions can be fluid, and special circumstances could force another project to perform the maneuver instead; the Mars Project Office is tasked with resolving any disputes of this nature.

NAVIGATION RESULTS

This section describes Maven's mission chronologically, with cruise, MOI, transition, and nominal science phases. Table 3 lists the major events of the mission.

Interplanetary Cruise Phase

For Maven's Type II interplanetary trajectory,[15] the nominal launch period was Nov. 18, 2013 through Dec. 7, 2013, with a contingency launch period extending through Dec. 23, 2013. The spacecraft launched at the open of the launch window on Nov. 18, 2013 at 18:28:00 UTC on a United Launch Alliance (ULA) Atlas V-401 with a Centaur upper stage. Spacecraft separation occurred at 19:20:45 UTC, and the solar panels began deployment approximately five minutes later. Maven was initially acquired by the DSN's complex in Canberra, Australia based on a launch vehicle trajectory provided before launch by ULA, and the first radiometric tracking data was recorded at approximately 20:11 UTC. The post-launch role of the navigation team was to provide a predicted trajectory that satisfied the DSN station pointing requirements (less than 0.032 deg pointing uncertainty for the 34 m antenna) for signal acquisition by the Madrid complex. OD analyses incorporated tracking data until approximately three hours before Madrid acquisition and delivered a predicted trajectory to the DSN approximately two hours before the start of the Madrid pass. The first data point during this pass was recorded on Nov. 19 at approximately 3:50 UTC. Pre-launch analyses showed that on this launch date the navigation team would still have been able to meet the DSN pointing requirement, even in the event of a delay of one hour in the initial Doppler data.[12] The launch phase executed nominally, and Maven was delivered to its outbound trajectory within desired tolerances. As determined by the second official OD solution, the differences between the estimated and targeted values of C_3 (or twice the energy), outbound right ascension, and outbound declination were 0.000237 km^2/s^2, 0.00165 deg, and 0.00298 deg, respectively. At approximately 18:24 UTC on Nov. 19, Maven slewed to its nominal early cruise attitude with its HGA boresight off-pointed from the sun by 60 deg. Telecom during this phase was performed with the forward LGA and would continue until the "late" cruise phase beginning in Feb. 2014.

Maven's launch and deployment biased its interplanetary trajectory such that it fulfilled the planetary protection requirement that the probability of the launch vehicle upper stage impacting Mars be less than 10^{-4}. The launch bias is evident in the body plane (B-plane)** mapping shown in Figure 4(a). The first deterministic propulsive maneuver, TCM-1, was designed to remove the launch aimpoint bias and test the main thrusters; it was performed 15 days after launch and was required to be at least 4.8 m/s in magnitude. TCM-2 was jointly optimized with TCM-1 for minimum Δv while maintaining the minimum magnitude constraint on TCM-1 and targeting MOI approach conditions with TCM-2. Performed on Dec. 3, 2013, TCM-1 imparted a Δv of approximately 4.842 m/s on Maven.

One day after TCM-1, the spacecraft team began powering up and checking out Maven's science instruments. From Dec. 11 to Dec. 16, Maven's IUVS was used in an attempt to observe comet ISON, which was all but destroyed in its close perihelion passage.†† Continuous tracking data ceased on Dec. 15, and the schedule of three eight-hour passes per week began for range and Doppler. Spacecraft operations in the remainder of December were largely devoted to instrument checkout; this period was mostly quiet from a navigation standpoint. Calibrations for the ACS thrusters and solar pressure modeling were performed on Jan. 6 and Jan. 8–20, respectively. The solar pressure calibration was a quiescent period at two fixed attitudes designed such that the dominant non-gravitational force on the spacecraft was solar radiation pressure. No other attitude adjustments and no thruster firings were performed during this period. Subsequent analyses led to the refinement of specular and diffuse reflectivity coefficients for the spacecraft's solar pressure model that was used in OD analyses during the remainder of cruise and in Mars orbit.

At 14:05 UTC on Feb. 12, Maven slewed to the late cruise attitude with its HGA Earth-pointed. For the remainder of cruise, tracking was primarily conducted through the HGA. The first ΔDOR data point was received on Feb. 16, and additional ΔDOR measurements were taken weekly until 60 days before MOI. To target its MOI approach conditions, Maven performed TCM-2 on Feb. 26 by firing its six TCM thrusters for about 19 seconds. The total velocity change was 0.671 m/s, which was within 18 mm/s of the targeted value. TCM-2 was the last maneuver performed prior to MOI (Figure 4(b)). TCMs-3 and 4 were statistical maneuvers and were not needed, and TCMs-5A and 5B, which were also canceled, were only to be used to avoid impact. These final two maneuvers would haven been executed only if an unacceptably low altitude

**The B-plane is the plane containing the center of Mars that is perpendicular to the Mars-relative incoming hyperbolic excess velocity.

††Information available at `http://www.nasa.gov/content/goddard/fire-vs-ice-the-science-of-ison-at-perihelion/` [accessed 25 Aug 2015].

had been predicted to occur during MOI or on subsequent periapses. The post-TCM-2 solutions were stable through MOI, as seen in the evolution of B-plane mappings for OD solutions with a data cutoff within one month of MOI (Figure 4(c)). Overall, Maven's cruise phase was nominal and successfully delivered the spacecraft to the desired pre-MOI state.

Table 3. Major Events Timeline

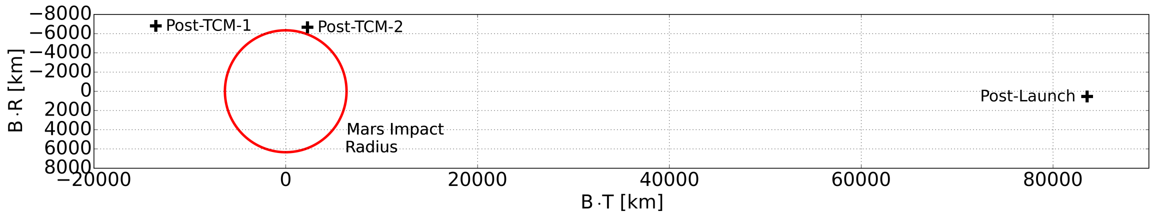
Event	Date(s)	Note
Launch	Nov. 18, 2013	Atlas V 401 from Cape Canaveral Air Force Station, Space Launch Complex 41
Trajectory Correction Maneuver #1	Dec. 3, 2013 18:00 UTC	Executed 15 days after launch; designed magnitude 4.8 m/s; reconstructed magnitude 4.842 m/s
Trajectory Correction Maneuver #2	Feb. 26, 2014 18:00 UTC	Targeted MOI conditions and executed 100 days after launch with a designed magnitude of 0.688 m/s, and a reconstructed magnitude of 0.671 m/s
Mars Orbit Insertion	Sep. 22, 2014 1:38 UTC	Capture into orbit with 34.9 hr period, 74.2 deg inclination, and periapsis altitude of 380.0 km
Transition Phase	Sep. 22 – Nov. 16, 2014	Included multiple maneuvers to reduce orbital period and periapsis altitude, APP deployment, instrument checkout, etc.
Comet Siding Spring Close Approach	Oct. 19, 2014	Passed within 130,000 km of Mars
Nominal Science Start	Nov. 16, 2014	
Deep Dip #1	Feb. 11 – 18, 2015	Periapses near dusk terminator; five maneuvers
Deep Dip #2	Apr. 17 – 23, 2015	Periapses near local noon; four maneuvers
Solar Conjunction	Jun. 3 – 25, 2015	Defined as period when sun-Earth-Mars angle is less than three degrees
Deep Dip #3	Jul. 8 – 15, 2015	Periapses near dawn terminator; three maneuvers
Period Correction Maneuver #1	Aug. 12, 2015 17:18 UTC	Designed with a magnitude of 31 m/s, and reconstructed with a magnitude of 30.897 m/s
Deep Dip #4	Sep. 2 – 10, 2015	Periapses near south pole; four maneuvers
Extended Mission Start	Nov. 16, 2015	

Mars Orbit Insertion

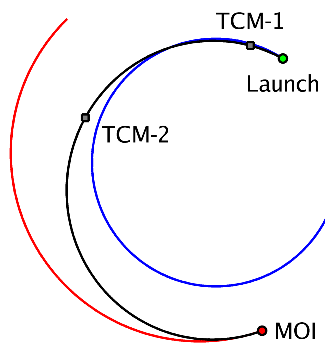
The MOI maneuver started as Maven approached Mars, 22 minutes before the ballistic closest approach, reducing the Mars-relative velocity and bringing the spacecraft into an elliptical orbit around Mars, as shown in Figure 5(a). The 1230 m/s maneuver was required to achieve a post-burn orbit with a 380$\pm$50 km periapsis altitude above a spherical Mars, an inclination of 75$\pm$1.5 deg and an orbit period of 35$\pm$5 hours. Because the burn lasted 33 minutes, a constant-rate pitchover about the orbit normal vector was necessary to maintain the thrust near the anti-velocity direction. MOI executed using the six main thrusters, with the TCM thrusters being used for attitude control; before execution of the main burn, these smaller thrusters were fired for 30 sec in a settling burn before the main thrusters started, in order to ensure propellant flow for the main thrusters.

Because MOI was the only non-recoverable critical event of the mission after launch, additional requirements were levied to make the maneuver tolerant to extreme low and high thrust levels, engine-out scenarios, and even an unplanned stop to the burn partway through execution. Like all maneuvers executed by Maven, the MOI command was designed by the spacecraft team to apply thrust until the Δv counted by the accelerometer reached the designed level, and then cut off. Minimum and maximum timer values were specified, such that if the accelerometer failed by counting too quickly, the burn would continue until at least the minimum time was reached, and if the accelerometer failed to count at all, the burn would stop at the maximum time. While normally set to a simple $\pm$10%, for MOI the timer values were selected to ensure: that Maven captured with an orbit period of at most 120 hours with an early stop and -3σ thrust; that -3σ thrust would not cause the maximum timer to trigger; and that with +3σ thrust hitting the maximum timer would not pose a Mars impact risk. Additionally, these timers were set to automatically extend if the system detected an engine-out scenario, allowing this contingency to be recoverable as well.

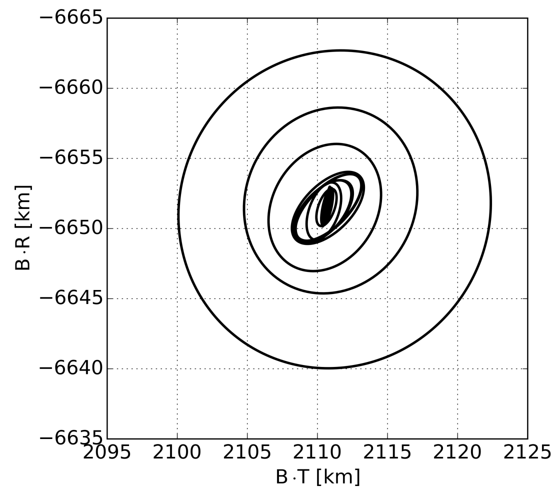
The MOI sequence was also designed to be tolerant to a complete failure of the burn partway through execution. A recovery mode was designed, whereby the vehicle, upon detection of a maneuver stop, would



(a) B-Plane mappings

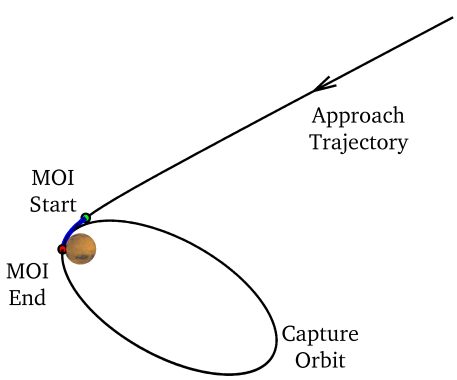


(b) Ecliptic projection in heliocentric frame

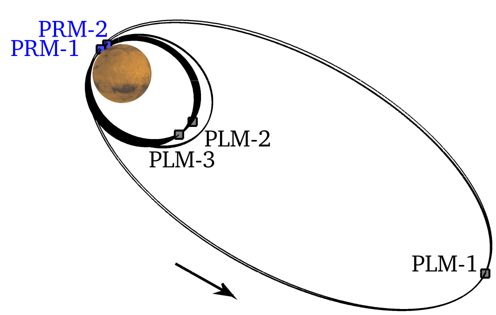


(c) Evolution of 3-sigma uncertainty in the B-plane from one month before MOI. Ellipse sizes decrease as time advances. Ellipses are centered about 150 km left of post-TCM-2 point.

Figure 4. Maven cruise trajectory as flown



(a) Approach, Mars orbit insertion, and capture orbit



(b) Transition phase trajectory and maneuvers

Figure 5. Mars orbit insertion and transition phase trajectories in the IAU Mars Pole frame. For clarity, only the initial position at each post-MOI maneuver is shown.

restart all systems, reorient to the attitude at the detected burn shut-down time, and continue burning until it had accumulated enough Δv to shut down as planned. It was calculated that the worst-case scenario would lead to a 14-minute duration for a complete restart. The requirements defined that the spacecraft should have an orbit period less than 120 hours in this scenario, even with -3σ thrust levels. Meeting this requirement demanded significant changes from an optimal MOI design: the maneuver time shifted forward by $\sim$3 minutes, the pitch angle and rate were updated to add a significant radial component, and the Δv increased by $\sim$16 m/s. Additional Δv to reduce the period from 120 hours had been allocated in the mission budget, so that the primary mission could be completed even in these contingency scenarios.

The final MOI design was 1230.4 m/s, and began at 1:38 UTC on Sep. 22, 2014. The maneuver executed nominally, achieving a 34.93 hour orbit period with a 380.00 km spherical periapsis altitude and an inclination of 74.21 deg. Post-MOI analysis by Navigation showed a total Δv of 1230.36 m/s and a mass loss of 998.2 kg.

Transition to Science

Following MOI, the operations team prepared the spacecraft for the primary science phase. This involved reducing the period to approximately 4.5 hours, lowering the altitude into the target density corridor of 0.05–0.15 kg/km^3, and deploying and testing the scientific instruments. The close approach of Comet C/2013 Siding Spring (CSS) on Oct. 19, 2014 within 130,000 km of Mars complicated this transition period, since plans had to be significantly altered five months before arrival, both to reduce particle impact risks and support science observations of this rare event.

The first three weeks were primarily dedicated to orbit-altering maneuvers (Figure 5(b)). A sequence of three periapsis-lowering maneuvers (PLMs) and three period-reduction maneuvers (PRMs) were planned. The first, PLM-1, was selected from a pre-built menu and executed at the second apoapsis after MOI, reducing the periapsis altitude to approximately 200 km, improving the efficiency of the PRMs while keeping the periapsis out of the atmosphere. At the third periapsis, two orbits after MOI, PRM-1 was planned. PRM-1 was a 455 m/s pitchover burn, executed on the main engines and centered on periapsis, that reduced the period to approximately 5.5 hours. Unfortunately, PRM-1 did not execute as planned, because the global variable specifying the accumulated Δv was not reset following MOI; this condition was not caught by the standard testing because the testing environment did not track the current spacecraft state, but instead started from a clean state. PRM-1 was executed one orbit later, with the start time reset and selected by the navigation team to ensure it was centered about the desired periapsis.

PRM-2 was scheduled a week after PRM-1, allowing time for a full sequence design process, in contrast with the pre-designed nature of PRM-1 and PLM-1. Executing in pitchover mode on the TCM thrusters, it was originally planned to target the desired 4.61 hour orbit period. However, the CSS safety plan required that the spacecraft was protected by the bulk of Mars at the time of maximum particle fluence, and thus the targeting plan was updated to achieve the desired orbit phasing, with the number of orbits between the maneuver and the encounter selected to get close to the desired orbit period.

The Δv for PLM-2, a fixed-velocity-direction maneuver, was then selected to achieve a periapsis density just outside the shallow[‡‡] edge of the corridor, 0.05 kg/km^3. This was originally planned four days after PRM-2, before the CSS encounter, and was left in place, since the targeted altitude was judged to be safe even if the comet induced an increase in atmospheric density, and leaving it in place allowed in-situ instrument checkouts to proceed, speeding entry into nominal science operations and supporting the opportunistic comet observations.

Two days later, PRM-3 was scheduled. This maneuver was not in the original plan, but was added because Monte Carlo simulations demonstrated that PRM-2 was not capable of ensuring acceptable phasing for the CSS encounter, particularly when the post-PLM-2 drag was considered. However, because PRM-2 performed well, and the density was well-behaved during this winter season, PRM-3 was canceled. Pre-encounter observations of the atmosphere proceeded. After shutting down critical systems and passing behind Mars at the time of maximum particle fluence, Maven resumed observations to determine the effects of the comet.[16]

[‡‡]The terms *shallow* and *deep* are used to indicate the low-density and high-density regions of the density corridor, respectively.

Table 4. Transition Maneuver Specifications

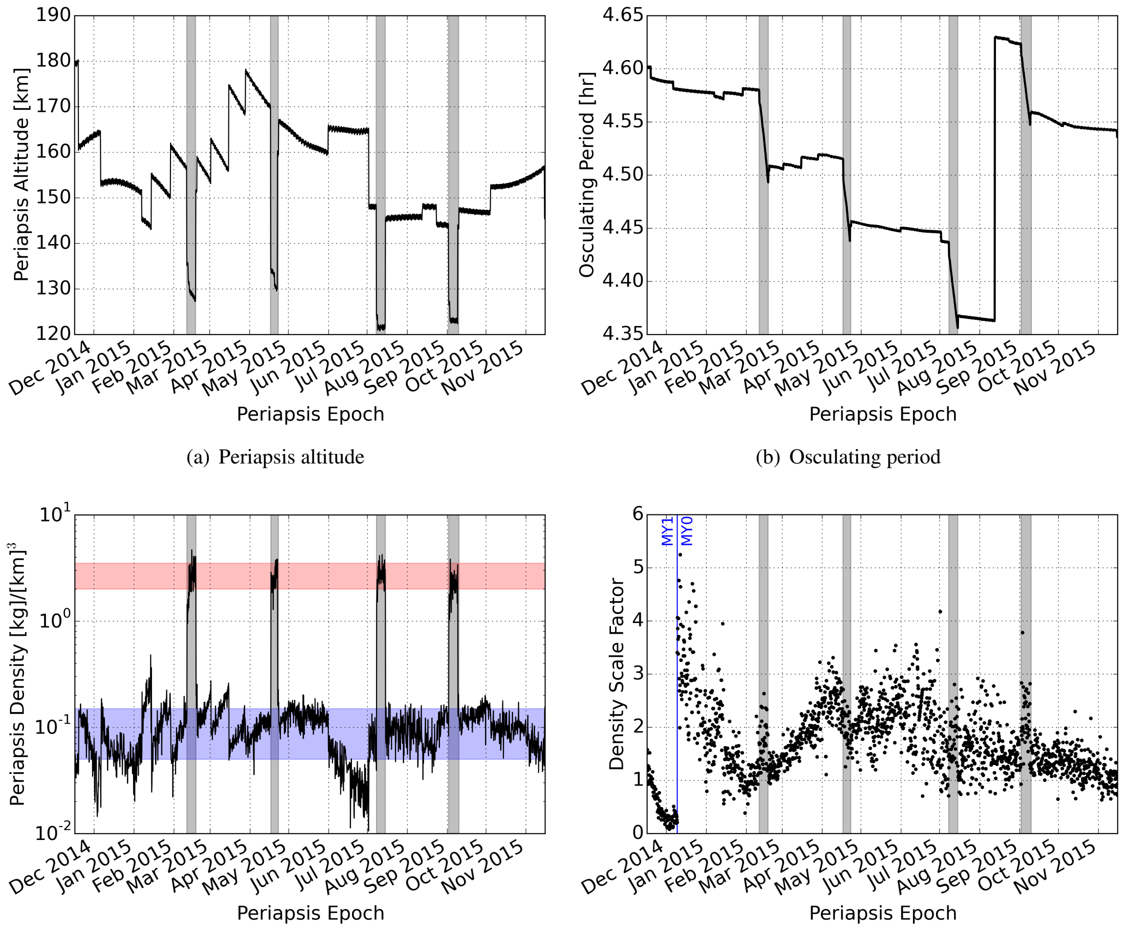
Name	Epoch (UTC)	Type	Purpose	Δv [m]/[s]
PLM-1	9/24/14 06:30	Menu-selected Δv, fixed anti-velocity direction	Reduce altitude to ∼200 km	10.0
PRM-1	9/27/14 21:32	Pre-designed pitchover	Reduce period to ∼5.5 hours	455.0
PRM-2	10/2/14 21:22	Fully designed Δv, velocity-point pitchover	Target CSS Phasing and orbit period of ∼4.6 hours	79.2
PLM-2	10/5/14 21:12	Fully designed Δv, fixed anti-velocity direction	Target ∼0.05 kg/km^3	2.6
PRM-3	10/9/14 19:52	Fully designed Δv, ± velocity direction	Clean-up for CSS phasing	**Canceled**
PLM-3	10/23/14 23:15	Selected from OTM menu	Target ∼0.15 kg/km^3	-2.7
PLM-4	10/29/14 22:02	Selected from OTM menu	Maintain corridor	**Canceled**

PLM-3 was then selected from the OTM menu to target near the deep end of the corridor (0.15 kg/km^3). Originally planned one week after PLM-2, it was delayed until Oct. 23, 2014, after the CSS encounter, because of concerns about comet-induced increases in atmospheric density, and the need to get an accurate trend of the post-encounter atmospheric behavior for targeting purposes. Because of the additional time required for the comet encounter activities, the transition phase was extended by two weeks, and PLM-4 was added to the schedule to arrest any drift in density that occurred during the lengthened period, ensuring that the spacecraft could be targeted to the density corridor at the start of the nominal science phase. Table 4 summarizes all transition-phase maneuvers.

Nominal Science Phase

Following the orbit transfer activities and instrument deployment and checkout activities of the transition phase, Maven's primary science phase commenced on Nov. 16, 2014. Because the navigation team's recent density estimates showed that Maven was now above the shallow (low density) edge of the density corridor (Figure 6(c)), it was decided to perform an OTM of -3.0 m/s on Nov. 19 at apoapsis of orbit 272, which lowered Maven's periapsis altitude by almost 20 km (see Figure 6(a) and Table 5). Shortly after this maneuver executed, Maven entered safe mode due to a problem with the reinitialization of PTE. During any safe mode, Maven remains continuously Earth-pointed and performs desats only when needed. Though safe mode is often a busy period for the spacecraft team, the simplified dynamics during this period mean that the navigation team does not generally encounter additional problems as long as tracking data is maintained, as it was in this case. Maven exited safe mode on Nov. 21 and resumed science operations on Nov. 30. To allow the spacecraft team to monitor PTE and respond to any problems, daily HGA passes were made through Dec. 23. The atmospheric density at periapsis decreased after OTM-1 and approached the shallow edge of the corridor. It was decided to cancel OTM-2 because the density was still within the corridor and because of large variations in the density estimates. As the density continued to decrease, OTM-3 was selected as a -1.8 m/s maneuver, executing on Dec. 6, and consuming an estimated 0.9 kg of propellant. For comparison, the average daily propellant use for desats during this period was 32 g.

On Dec. 15, the navigation team switched from Mars-GRAM MY1 to MY0 as this gave better agreement with predicted density trends. The atmospheric density at periapsis continued to decrease until OTM-8, a -0.9 m/s maneuver performed on Jan. 7, 2015. The selection of MY0 was vindicated in Jan. 2015 when MY0 predicted a rapid increase in density that was confirmed by the navigation team's own density estimates. The estimated Mars-GRAM scale factor approached 1.0 by the end of the month (Figure 6(d)). After OTM-8, the density increased rapidly enough that two periapsis-raising OTMs were required in the remainder of the month (OTM-9 and OTM-11). On Jan. 25, Maven reported that both motor controllers for the APP had experienced an anomaly. Maven was commanded to assume an Earth-pointed attitude and communicate on its HGA while the problem was addressed. The problem was traced to APP vector tracking in a particular sun-pointed attitude. After a software parameter update by the spacecraft team, the APP was recovered on Jan. 30, and nominal science operations resumed on Feb. 3.



(a) Periapsis altitude

(b) Osculating period

(c) Periapsis density

(d) Density scale factor

Figure 6. Maven science orbit evolution. Shaded vertical regions indicate deep dip periods. Shaded horizontal regions indicate nominal and deep-dip density corridors.

The first deep-dip campaign (DD1), originally planned for January, occurred from Feb. 9 through Feb. 18, 2015, with periapses near the dusk terminator, as seen in Figure 7. On Feb. 9, the Maven team selected the first walk-in maneuver, DDM-A1, as a -3.3 m/s burn to be performed at apoapsis of orbit 712 on Feb. 11 (Figure 8). The maneuver reduced the periapsis altitude by about 20 km to 135 km and increased the periapsis density to 1.5 kg/km^3. This maneuver magnitude was a compromise between safely getting to the deep-dip corridor and balancing the uncertainties in density across such a large altitude change. To target the required deep-dip density corridor of 2.0–3.5 kg/km^3, DDM-A2 was selected as a -0.6 m/s maneuver. Although Maven achieved the shallow end of the corridor, a -0.2 m/s DDM-A3 was selected to put Maven in the deep end of the corridor. Due to the mission requirement that Maven be able to perform a maneuver every day if necessary during deep dips, the navigation team delivered predicted and reconstructed trajectories daily, and held meetings daily with the science and spacecraft teams to determine if a DDM was necessary. After a nominal period in the deep-dip corridor, walk-out maneuvers DDM-A8 and DDM-A9 placed Maven back into the nominal science density corridor on Feb. 18. The five deep-dip maneuvers consumed about 4.68 kg of propellant; the average daily propellant consumption for desats during DD1 was approximately 74 g.

The OD process during deep dips is more challenging than during nominal science operations. The lower periapsis altitude heightens the effects of mismodeled atmospheric perturbations and degrades the quality of orbit estimation. Generally each OD solution covers no more than three deep-dip periapses, whereas five

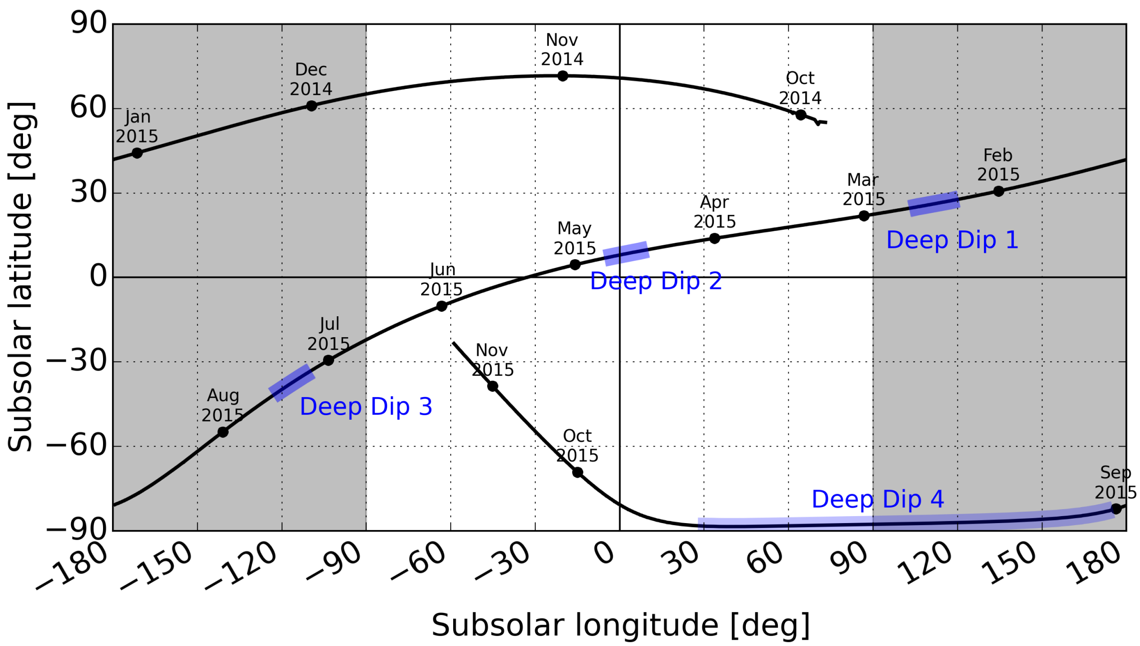


Figure 7. Periapsis location evolution from MOI through the end of the nominal science phase

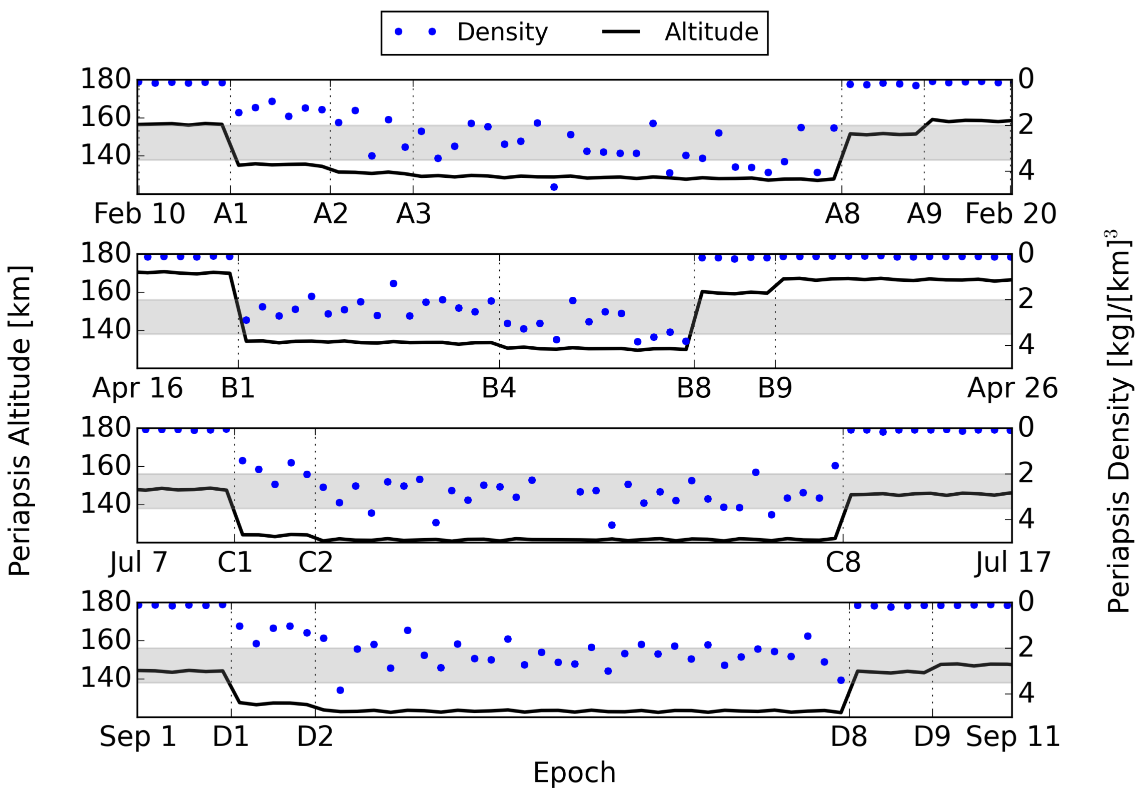


Figure 8. Altitude and density at periapsis during the deep dips. DDM epochs indicated on horizontal axis. Deep-dip density corridor indicated by shaded horizontal regions. Corridor applies only to density, not altitude.

Table 5. Orbit Trim Maneuvers

Name	Reconstructed Epoch [ET]	Orbit Number	Planned Velocity Change [m]/[s]
PLM-3	2014/10/23 23:15:15	136	-2.7
OTM-1	2014/11/19 01:31:03	272	-3.0
OTM-3	2014/12/06 06:44:17	362	-1.8
OTM-8	2015/01/07 03:40:47	529	-0.9
OTM-9	2015/01/14 14:05:20	568	1.8
OTM-11	2015/01/29 11:10:00	646	1.8
DDM-A1	2015/02/11 01:33:49	712	-3.3
DDM-A2	2015/02/12 04:57:07	718	-0.6
DDM-A3	2015/02/13 03:44:34	723	-0.2
DDM-A8	2015/02/18 01:22:29	749	3.9
DDM-A9	2015/02/18 23:53:05	754	1.2
OTM-16	2015/03/01 16:48:28	811	1.5
OTM-18	2015/03/15 14:26:24	885	3.0
OTM-20	2015/03/28 13:58:02	954	1.5
DDM-B1	2015/04/17 03:43:05	1058	-5.7
DDM-B4	2015/04/20 03:22:43	1074	-0.4
DDM-B8	2015/04/22 08:49:14	1086	4.8
DDM-B9	2015/04/23 07:03:53	1091	1.2
OTM-29	2015/05/31 16:26:04	1298	0.9
OTM-33	2015/07/02 04:41:43	1468	-2.7
DDM-C1	2015/07/08 02:44:41	1500	-3.9
DDM-C2	2015/07/09 00:50:54	1505	-0.4
DDM-C8	2015/07/15 01:39:23	1538	3.9
OTM-41	2015/08/23 15:06:11	1752	-0.6
DDM-D1	2015/09/02 01:47:23	1801	-2.7
DDM-D2	2015/09/03 00:50:31	1806	-0.6
DDM-D8	2015/09/09 03:22:26	1838	3.3
DDM-D9	2015/09/10 02:09:20	1843	0.6
OTM-47	2015/10/04 13:43:32	1972	0.9
OTM-53	2015/11/15 09:59:43	2193	-1.8
Total velocity change			61.6

to ten periapses may be covered in a typical reconstruction of the nominal science orbit. During DD1, the difficulty resulted in successive reconstructed trajectories exhibiting a maximum offset of more than 500 m whereas the offset during nominal operations is typically under 100 m. Even during the deep dips, however, the 3σ requirement to reconstruct the orbiter's position to within 3 km was easily met.

Following DD1, the atmospheric density at periapsis increased. OTM-16 was executed Mar. 1 to return the spacecraft to the shallow end of the density corridor. Its magnitude of 1.5 m/s was selected to allow some margin and reduce the number of needed future OTMs. The atmospheric density continued to increase, and OTM-18 was executed Mar. 15. The selected magnitude of 3.0 m/s minimized COLA concerns with Phobos and also returned Maven to the shallow edge of the density corridor. OTM-20 was executed Mar. 28 as a 1.5 m/s maneuver after several periapses with atmospheric density estimates near the deep end of the corridor. On Apr. 3, a battery voltage fault protection check problem put Maven in safe mode. It was successfully returned to nominal operations on Apr. 10, and the issue did not impact the subsequent deep-dip campaign.

The second deep-dip campaign (DD2), originally scheduled to begin Apr. 7, featured periapses near local noon and was purposely delayed to Apr. 14, which resulted in a more favorable location from a science perspective. The first walk-in maneuver was selected as a -5.7 m/s burn executed on Apr. 17 at the apoapsis of orbit 1058. The maneuver reduced the periapsis altitude by 36 km to 134 km and increased the periapsis density to 2.7 kg/km^3, placing Maven in the middle of the deep-dip corridor. Because the navigation and spacecraft teams experienced success during DD1, the project had confidence in this more ambitious DDM-B1 maneuver selection. Once in the corridor, the density was predicted by Mars-GRAM MY0 to trend up, but was in reality trending downward. As Maven was already at the shallow end of the deep-dip density corridor, maneuver DDM-B4 was designed to push Maven deeper into the corridor. This -0.4 m/s maneuver was executed on Apr. 20. After the remaining orbits in DD4 were executed, walk-out maneuvers DDM-B8 and DDM-B9 on Apr. 22 and Apr. 23 returned Maven to the nominal science density corridor. The four maneuvers consumed about 6.13 kg of propellant.

Like in DD1, the navigation team during DD2 again faced difficulties achieving a good fit of the tracking data for multi-orbit reconstructions, and this led to increased offsets between successive trajectories, unrealistically high post-periapsis desat magnitude estimates, and an inflated solar pressure scale factor. Because the Δv from a single drag pass at deep-dip altitudes is often greater than 100 mm/s, an accurate atmosphere model is crucial for a good orbit fit. The Mars-GRAM model does not capture every structure in the atmosphere nor all temporal variations. Among other effects, this mismodeling can result in an offset between the time of maximum density in the dynamic model and the actual time of maximum density as observed by Maven's onboard inertial measurement unit. In an attempt to account for the timing offset, equal and opposite impulsive maneuvers were added on each side of periapsis with apriori standard deviations on the order of 5.0 mm/s. This effectively allows a timing shift in the drag pass without affecting the density estimate since the orbital energy is essentially unchanged. This strategy was successfully implemented during DD2 and subsequent deep dips for problematic trajectory arcs.

Following DD2, Navigation's periapsis density estimates were stable; in fact, the next maneuver after DDM-B9 was OTM-29, which was not executed until May 31. From a density perspective, OTM-29 was not needed, but by moving Maven to the shallow edge of the density corridor with the 0.9 m/s maneuver, extra margin was created for the 24 days when Maven would be behind the Sun, a configuration called solar conjunction. In this geometry—defined to occur when the Sun-Earth-Probe (SEP) angle is less than 3 deg—the tracking data quality is significantly degraded, and the spacecraft team is unable to uplink new ephemerides; therefore, Maven cannot meet its pointing requirements. Additionally, there is no atmospheric density corridor control. Because of this, and even though the periapsis density was expected to remain constant or decrease slowly, Maven was pre-positioned with OTM-29 to the shallow end of the density corridor as a precaution against unexpectedly high densities. From Jun. 3 to Jun. 25, the SEP angle was less than 3 deg, and from Jun. 7 to Jun. 21, the SEP angle was less than 2 deg. The minimum angle during conjunction of 0.62 deg occurred on Jun. 14. During these two weeks, a command moratorium was in effect for the spacecraft. Fortunately, solar conjunction occurred during the low density season on Mars, and a slow decrease in periapsis density was observed, as expected before conjunction. For the entirety of this period, the two HGA passes were executed weekly to downlink spacecraft and instrument data. Additionally, desats occurred near apoapsis during this phase, and one desat was also specifically commanded before each HGA pass. Following solar conjunction, low atmospheric densities were observed, so OTM-33 was selected to decrease Maven's periapsis altitude by 17 km to 146 km.

The third deep-dip campaign (DD3) occurred from Jul. 7 to Jul. 15. The first walk-in maneuver, DDM-C1, was executed at the apoapsis of orbit 1500 on Jul. 8. The -3.9 m/s maneuver decreased Maven's altitude by 24 km to 122 km and increased the periapsis density to 1.7 kg/km^3. The second walk-in maneuver, DDM-C2, was executed Jul. 9 as a -0.4 m/s maneuver. This conservative selection achieved a periapsis density of 2.75 kg/km^3 and further decreased the periapsis altitude by 2.5 km. After nominal operations in the deep-dip corridor, one walk-out maneuver, DDM-C8, was executed Jul. 15 and returned Maven to the middle of the nominal density corridor with a density of 0.08 kg/km^3 and an altitude of 143 km. The three maneuvers consumed about 4.06 kg of propellant, and the average daily desat consumption was 70 g.

Because the periapsis segment of Maven's orbit passes through Mars' appreciable atmosphere, the resultant drag reduces Maven's orbital energy and, therefore, its orbital period; the trend is even more pronounced during deep dips (Figure 6(b)). The nominal period of 4.5 hr was originally chosen as a compromise between the short period needed to provide global coverage of Mars and the long period more suited for accurate apoapsis science observations. The first period correction maneuver, PCM-1, was designed to increase the period since it had decreased to 4.37 hr. The 31 m/s maneuver executed at the periapsis of orbit 1696 on Aug. 12, 2015 at 17:18 UTC using a 25% duty cycle, resulting in a burn duration of about 18 min. Because it was executed at periapsis, nominal science operations halted for two days and resumed on Aug. 14. PCM-1 increased Maven's period to 4.63 hr, apoapsis altitude by about 515 km, and its periapsis altitude by about

2 km. The observed atmospheric density trends after PCM-1 differed from the MY0 model, which was predicting an increasing density, and were actually decreasing. The next maneuver, OTM-41, was executed on Aug. 23, the last opportunity before the fourth deep-dip (DD4) campaign.

The final deep-dip campaign of the primary mission occurred from Sep. 1 to Sep. 9, with periapses near the Martian south pole (Figure 7). (Due to the rectangular projection used in Figure 7, the extent of DD4 appears exaggerated.) Despite being in a COLA season with MEX and MRO, there were no collision concerns. The first walk-in maneuver, DDM-D1, was executed at the apoapsis of orbit 1801 on Sep. 2 with a magnitude of -2.7 m/s. This lowered Maven's periapsis altitude by 17 km to 126 km and increased the periapsis density to 1.03 kg/km^3. The second walk-in maneuver, DDM-D2, executed at the apoapsis of orbit 1806 on Sep. 3, increased the periapsis density to 1.55 kg/km^3, and lowered the periapsis altitude by an additional 4 km. Following another nominal campaign, the walk-out maneuvers DDM-D8 and DDM-D9 were executed on Sep. 9 and Sep. 10 and ultimately returned Maven to the nominal density corridor with a periapsis density of 0.11 kg/km^3 and an altitude of 146 km. These four maneuvers consumed 3.50 kg of propellant, whereas the average daily desat consumption was 51 g.

Following DD4, the atmospheric density at periapsis increased until Maven reached the deep edge of the corridor. At this time, OTM-47 executed on Oct. 4 to return Maven to the middle of the density corridor. Over the next month, the atmospheric density at periapsis slowly decreased, and, more than a month later, OTM-53 executed on Nov. 15 when Maven was at the shallow edge of the corridor. For operational reasons and to avoid conflicts with future targeted Phobos observations, a larger magnitude of -1.8 m/s was selected to move Maven slightly deeper in the corridor. The first targeted set of Phobos observations were conducted Nov. 10.

The drag Δv per pass was generally observed to be between 1 mm/s and 10 mm/s at nominal science altitudes. The drag Δv per pass was observed to be between 80 mm/s and 180 mm/s at deep-dip altitudes. During Maven's first Earth year of science operations at Mars, this amounted to around 10 m/s of Δv per deep dip. Trajectory errors due to uncorrected wave variations in the atmosphere are inflated at these lower altitudes during the deep dips. The continuous DSN data does not help with this, since only net Δv is observable with Doppler. Although all requirements are being met, performance could likely improve with the use of telemetry derived observables and some higher-order atmospheric corrections.[14]

FUTURE OPERATIONS

Maven's first extended mission (EM-1) officially commenced on Nov. 16, 2015 and will allow Maven to accumulate at least one Mars year of observations. Maven will continue its nominal science operations during this time, potentially adding two deep dips and close observations of Mars' largest natural satellite, Phobos. Also of note during EM-1 are Maven's degraded navigation accuracy capabilities due to decreased spacecraft mass. This decreased mass results in an increased atmospheric drag perturbation on the spacecraft's trajectory. In addition, it is predicted that in the latter portion of EM-1 there will be more atmospheric variability, resulting in more OTMs and thus more propellant consumption.

Maven's extended science phase is expected to continue until its propellant has decreased to near the total amount needed for communications relay operations for a specified number of years, although this transition may occur much sooner at the behest of the Mars Program Office. At that point, Maven will transition to a higher relay orbit in which it will continue science operations and function as a relay for surface assets with the Electra UHF link. The relay orbit is expected to be similar to the science orbit, except with a periapsis altitude above 200 km.

CONCLUSION

The navigation group, in concert with others on the Maven team, successfully and accurately guided Maven from Earth to Mars for orbit insertion, and enabled Maven to meet the mission requirements during the nominal science phase. During interplanetary cruise, thanks to an accurate launch injection, accurate maneuver execution, and accurate navigation solutions, no statistical trajectory correction maneuvers were required after the first two deterministic maneuvers. At Mars, all navigation requirements were met in an orbital regime unique for the primary phase of a Mars orbiter. Due to a persistent awareness of collision concerns with other spacecraft in the selection of standard orbit trim maneuvers, no explicit collision avoidance maneuvers were required during Maven's first Earth year at Mars. Overall, the navigation team's performance helped Maven achieve its desired science orbit and continues to meet the mission's ongoing requirements. The precise navigation has enabled the science team to investigate Mars' upper atmosphere as never before, and will allow significant improvements to Mars atmosphere models, and determinations of the mechanisms and rate of loss of volatiles to space. These findings will increase our understanding of Mars' climate history, the stability of liquid water on Mars, and the potential for past or present life.

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