# NAVIGATION CHALLENGES IN THE MAVEN SCIENCE PHASE

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***Abstract:*** *The MAVEN spacecraft will explore Mars' upper atmosphere. The primary science phase will last one (Earth) year, during which the spacecraft will be in an elliptical 4.5 hour orbit at an inclination of 75 degrees. The 75 degree inclination results in the orbit periapsis oscillating between ±75 degrees latitude, thus naturally covering most Mars latitudes during the primary mission. The orbit will be controlled via maneuvers so that the maximum orbit density remains in a density corridor. This results in the MAVEN science phase being in a light aerobraking type orbit of around 160 km for an extended period. In addition, the mission has significantly less tracking data than aerobraking phases of other missions, and even less than other NASA Mars orbiter primary phases. This results in significant challenges for the Navigation Team. They can be summarized as a difficulty in determining the current density profile, which maps into degraded trajectory predictions and less accurate control over the spacecraft location in the targeted density corridor via maneuvers. This paper describes these challenges and the Navigation Team's plans to meet them.*

***Keywords:*** *Spacecraft, Navigation, MAVEN, Accuracy, Mars.*

## 1. Introduction

The Mars Atmosphere and Volatile EvolutioN Mission (MAVEN) is a future National Aeronautics and Space Administration (NASA) Mars orbiting spacecraft whose purpose is to study the atmosphere ([1]-[3]). It was part of NASA's Mars Scout Program. The project is managed by Goddard Space Flight Center (GSFC), with Lockheed Martin (LM) building the spacecraft and the Jet Propulsion Laboratory (JPL) performing the navigation. At first glance, the navigation might appear to be standard compared to the previous Mars orbiters. However, there are several unique features of the mission design that make navigation particularly challenging in the science phase. This paper describes the science phase navigation requirements, the differences between this orbiter and previous NASA Mars orbiters and the resulting challenges.

MAVEN will explore the planet's upper atmosphere, ionosphere and interactions with the sun and solar wind. Its nominal launch period extends from 18 November 2013 to 7 December 2013. It will be in a Type II trajectory, reaching Mars in late August 2014. A five-week transition phase follows, during which science instruments will be checked out and a series of propulsive maneuvers will transition the spacecraft (S/C) into the nominal science orbit. The primary science phase will last one (Earth) year, during which the spacecraft will be in an elliptical 4.5 hour orbit at an inclination of 75 degrees. This 75 degree inclination results in the orbit periapsis oscillating between ±75 degrees latitude, naturally covering most Mars latitudes during the primary mission. The orbit will be controlled via maneuvers so that the maximum orbit density remains in one of two density corridors. The nominal corridor is 0.05 kg/km$^3$ to 0.15 kg/km$^3$. This results in a periapsis altitude around 160 km. However, the altitude will vary significantly based on the latitude, Mars season and actual observed atmosphere behavior. Five times during the science phase, MAVEN will maneuver to a higher density corridor (2 kg/km$^3$ to 3.5 kg/km$^3$) to perform science for five days.

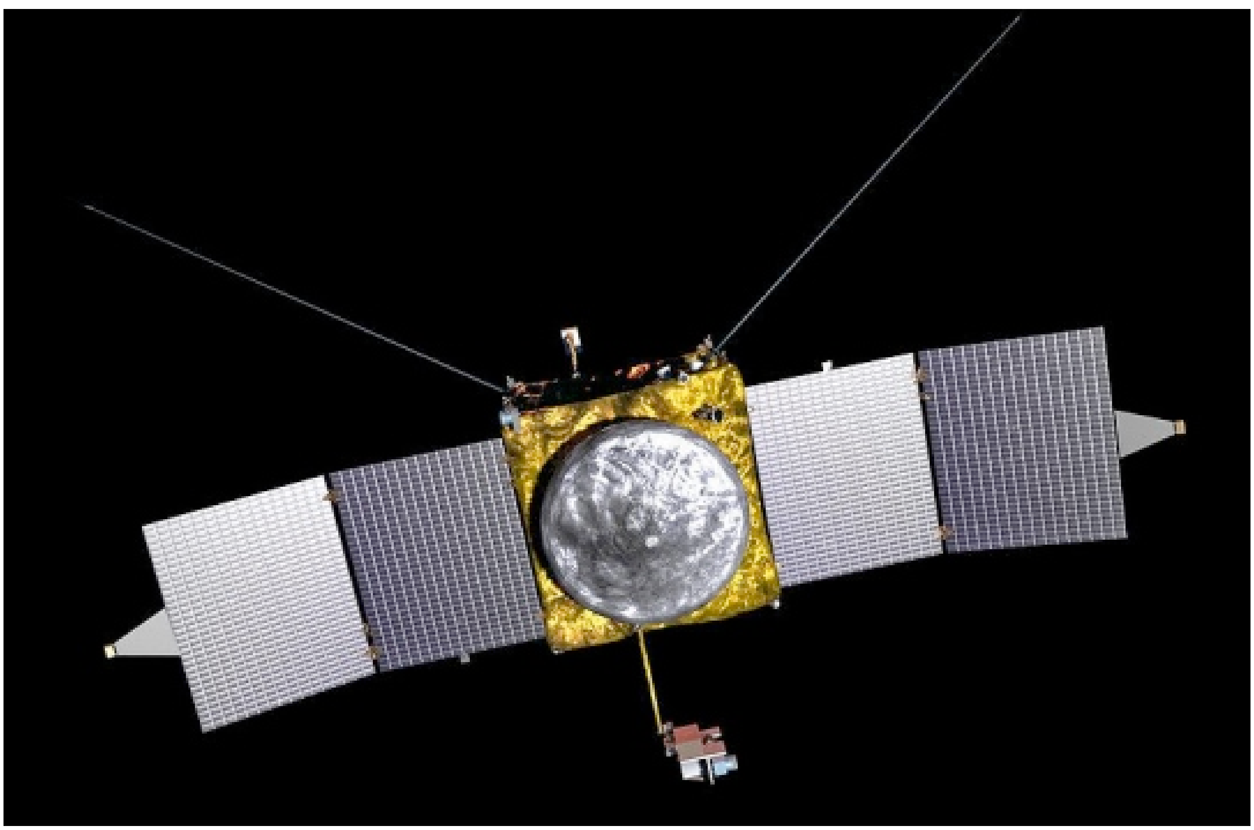

**Figure 1: MAVEN Spacecraft**

The MAVEN spacecraft (Figure 1) looks similar to Mars Reconnaissance Orbiter (MRO) and Mars Global Surveyor (MGS). It has a standard box shaped bus with solar arrays on either side. Unlike MRO and other Mars orbiters, the high gain antenna (HGA) is fixed on the spacecraft. (The HGA boresight is pointing out of the page, along the spacecraft +Z-axis.) Thus most communications with Earth during the science phase require rotating the entire spacecraft, preventing desired science measurements. Consequently Earth HGA communication is minimized during the science phase. The only articulating component of the spacecraft is the Articulated Payload Platform (APP). It houses several instruments and is seen at the end of the boom at the center bottom of Figure 1. (The boom extends out from the bus along the spacecraft +X-axis. The +Y-axis is along the solar panels, completing the right-handed coordinate frame.) However, the APP is ignored in the navigation analyses. Like MRO and MGS, the spacecraft and solar array placement are designed to give an aerostable attitude that is used during parts of the science phase.

## 2. Comparison of MAVEN with Mars Reconnaissance Orbiter

A key feature in the efficiency of the MAVEN project, including navigation, is its inheritance from Mars Reconnaissance Orbiter (MRO) and other previous Mars orbiters ([4]-[6]). From a navigation perspective, the MAVEN science phase may be succinctly described as a light aerobraking phase with science requirements and limited Deep Space Network (DSN) tracking data. This results in significant differences from MRO navigation. The light aerobraking phase necessitates an aerobraking like operations process similar to MRO. However, the science requirements result in dramatically tighter accuracy requirements than for MRO aerobraking – although they are partially offset by the smaller atmospheric drag. The limited DSN tracking results in a less frequent navigation product delivery schedule, similar to the MRO science phase. Table 1 summarizes the principle differences between MAVEN and MRO navigation.

**Table 1: Comparison of MAVEN Science Phase with MRO**

| | **MRO Aerobraking** | **MAVEN Primary Mission** |
|---|---|---|
| *Purpose* | Orbit change | Science |
| *Drag Pass $\Delta V$* | 3 m/s | 0.006 m/s (0.15 m/s in deep-dip) |
| *Accuracy: Trajectory* | 225 second timing error | 20 second timing error |
| *Science* | None | Yes (on other 6 orbital elements) |
| *Tracking Data (Doppler)* | Continuous (HGA) | 7 hours/day (LGA) |
| *Delivery Schedule* | Multiple per day (4.5-hr orbit)<br>(In Science: 2/week [predict]) | 2/week (predict), 1/week (reconst.)<br>Deep-Dip: 1/day |
| *Density (Predict) Model* | • Doppler atmosphere estimate every orbit<br>• S/C orientation is the same for each drag pass<br>• S/C component shadowing is the same for each drag pass. (No shadowing.) | • Doppler atmosphere estimate for only 20% of the orbits<br>• S/C orientation changes with periapsis passes<br>• S/C component shadowing varies with periapsis passes. (Shadowing exists.) |

## 3. Operations Timelines

### 3.1. Deep Space Network Support: Radiometric Tracking Data

Since the MAVEN spacecraft does not have an ultra-stable oscillator (USO), navigation will rely on 2-way Doppler data during the science phase. The MAVEN DSN coverage is 8 hours per day, yielding 7+ hours of 2-way Doppler per pass.[1] Two additional 8 hour DSN passes have been added on Sunday and Wednesday to decrease navigation's sensitivity to lost tracking data, and to allow more flexibility in navigation and other team scheduling. The 8 hour DSN pass is a recent increase over the previous minimal 6 hour pass (5+ hours of Doppler).[2] This also reduces navigation's sensitivity to possible DSN related problems, including weather.

Since MAVEN does not have a gimbaled high-gain antenna (HGA) like the previous Mars orbiters, the entire spacecraft must turn when it wants to communicate with Earth. Since this results in the loss of science data, the HGA Earth pointed modes only occur twice per week, on Tuesday and Friday. Furthermore, the spacecraft only points towards the Earth for approximately 5 of the 8 hours during these "HGA" passes. All other DSN contact will be on the low-gain antenna (LGA). In general, navigation will perform its analyses on the LGA pass before the HGA pass. Navigation will deliver its products in time for them to be processed into sequence products and uplinked during the HGA pass.

Note that this DSN coverage is minimal compared to the continuous coverage standard for the aerobraking phases of previous Mars missions (Mars Global Surveyor (MGS), Mars Odyssey 2001 (ODY), Mars Reconnaissance Orbiter (MRO)). In fact, it is less than that for the higher orbits of the MGS, ODY and MRO primary science phases. This will result in significantly reduced accuracies in the reconstructed trajectories. However, this is acceptable for the suite of science experiments on the MAVEN spacecraft. The biggest challenge is to meet the accuracy requirements on the predicted trajectories.

As a final note, due to the larger atmosphere perturbations, the DSN coverage during the brief deep-dip periods is continuous.

### 3.2. Navigation Covariance Analysis and Filter Model

The navigation accuracy requirements are divided into two parts: reconstruct and predict accuracies. To determine if navigation could meet the requirements, covariance analyses were performed with the filter setup shown in Table 2. The analyses were performed for representative days though out the science phase, including regions of degraded orbit determination (OD) due to geometry.

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[1] Due to Earth-Mars two-way light time, DSN lock up, etc., the amount of Doppler data received per pass will be up to 1 hour less than the DSN allocated pass length.

[2] As a result of navigation studies, previous Mars orbiter experience and the need to estimate for the atmospheric drag during the pass, navigation requires over one orbit of Doppler (~5 hours) hours).

**Table 2: Science Phase Filter Assumptions**

| Error Source | Estimate or Consider | A Priori Uncertainty (1σ) | Correlation Time | Update Time | Remarks |
|---|---|---|---|---|---|
| **X-Band 2-way Doppler** | - | 0.2 mm/s (60 sec) | - | - | At least a 5 hr data arc |
| | | | | | |
| **Epoch state pos (km)** | - | 100 km | - | - | |
| **Epoch state vel (km/s)** | - | 0.1 km/s | - | - | |
| | | | | | |
| **Solar Radiation Overall Scale Factor (%)** | Est.<br>Stochastic | 10%<br>10% | White | 18 hours | |
| **Density Scale Factor (%)** | Est.<br>Stochastic | 13.3%<br>35% | White | Per Orbit | Est. for reconstruct only |
| **Small Forces (DESAT)** | Stochastic | 0.67 mm/s | White | Per Orbit | Filter |
| **Orbit Trim Maneuvers** | - | - | - | - | Not included |
| | | | | | |
| **Atmosphere Overall Scale Factor (%)** | Con. | 13.3% | - | - | Only apply for predict mappings |
| **Small Forces (DESAT)** | Con. | 0.67 mm/s | - | - | Only apply for predict mappings |
| **Station Location** | Con. | Full covariance | - | - | |
| **Media** | Con. | Ion: 15/65 cm<br>Trop: 1/4 cm | - | - | Night/Day<br>Dry/Wet |
| **Earth Orientation** | Con. | 10cm | - | - | X/Y-pole, UT1 |
| **Mars/Earth Ephemeris** | Con. | Full covariance | - | - | DE414 |
| **Mars Gravity** | Con. | 10x10 covariance, 20*formal | - | - | Include GM |

The density (scale factor) is the driving error source, overwhelming all other sources. The orbit-to-orbit 3σ variation is assumed to be 105%, which is consistent with past Mars orbiter assumptions and supported by their observations. The density "bias" error, or error in the mean density, has been increased from the 30% used on previous missions to 40%. A predict model must be generated for each predicted trajectory delivery, of which the main component is the current mean density. Unlike other missions, due to the decreased DSN coverage and placement of the HGA passes, navigation may only have one recent density estimate per day for use in deriving the predict model. Furthermore, the varying orientations of the spacecraft as it goes through the drag pass (discussed below) can cause inconsistencies in density estimates.

Navigation is using the Mars-GRAM 2005 (MG05) Mars atmosphere model with TES "MapYear" of 1, as described in [7]-[8]. Navigation will actually estimate the scale factor that must be applied to the MG05 model to get the correct density or drag $\Delta V$.

## 3.3. Navigation Accuracy Requirements and Capabilities

Navigation is required to deliver reconstructed trajectories that are accurate within 3 km. This can be accomplished for any combination of DSN complexes in the "daily" passes. A reconstructed accuracy could be worse than 3 km if a DSN pass is lost. However, this contingency case is excluded in the mission 3 km requirement. Table 3 summarizes the covariance analysis results using a 3-day Doppler data arc. The top row gives the DSN daily complex schedule, where "G" refers to Goldstone, "M" refers to Madrid, and "-" refers to a missed DSN pass. The "required 3σ density" refers to the 3σ density error assumption that would be required if the 3 km accuracy was to be met.

**Table 3: Navigation Reconstruct Capabilities, km**

| 3-Day DSN Schedule: | | | GGG | GMM | G-G | G-M | Notes |
|---|---|---|---|---|---|---|---|
| 3 km accuracy reqt | Fly-Z | OD 3σ Error | 1.5 | 3.0 | 4.2 | 6.5 | All nominal cases meet requirement |
| | | Required 3σ Density | | | 72% | 45% | Non-Doppler orbit density accuracy needed to meet requirement |
| 3 km accuracy reqt | Fly-Y | OD 3σ Error | 0.7 | 1.1 | 1.5 | 2.3 | All cases meet requirement |
| | | Required 3σ Density | | | | | Nominal 105% 3σ orbit variation accuracy is adequate for all cases |

The predict requirements are more involved, and determine the navigation weekly operations schedule. The predict requirements are specified in terms of six orbital elements (a, e, i, ω, Ω, and mean anomaly or down-track timing error). This is to reduce correlations in certain elements, and to simplify the mapping of accuracies to spacecraft pointing errors as defined by science requirements. The shape and orientation of the spacecraft orbit (and their errors), as defined by the first five orbital elements, do not change quickly with time. However, the error in the knowledge of where the spacecraft is in that orbit is much more uncertain: that is, the mean anomaly, time from periapsis, or down-track position/timing error. Thus the predict accuracy requirements are divided into two parts:

- Navigation shall predict the periapsis uncertainty to less than 20 seconds of periapsis passage time.
- Navigation shall predict the orbital elements to the following accuracies for at least 9.5 days in the nominal orbit and 2.8 days in the deep-dip orbit.
    - Semi-major axis: +/- 50 km
    - Eccentricity: +/-0.025
    - Inclination: +/-0.20 deg
    - Longitude of Ascending Node: +/-0.04 deg
    - Argument of periapsis: +/-0.3 deg

Different science instruments prefer different spacecraft orientations. To simplify operations, the nominal sequence has divided each orbit into four segments, related to the type of science observations desired: periapsis, "outbound" side, apoapsis, "inbound" side. The spacecraft may be in a different orientation for each of these segments. Operationally the same orientation will be used for both side segments, resulting in three distinct orientations per orbit. Furthermore, each sequence may have two different sets of three orientations: each set may be interchanged between even and odd orbits. From a navigation perspective, the critical orientation is around periapsis since it determines the atmospheric perturbation on the orbit. There are four possible periapsis orientations:

- Fly-Y: minimal spacecraft surface area in the direction of the atmospheric drag flow. (S/C +/-Y-axis in (Mars relative) velocity direction, +X towards nadir. So solar arrays are seen edge-on by the atmosphere.)
- Fly-Z: maximal spacecraft surface area in the direction of the atmospheric drag flow. (S/C –Z-axis in velocity direction, +X towards nadir. So the back of the inner solar arrays are seen flat-on by the atmosphere.) From a navigation perspective, it is similar to the "drag pass" orientation for the deep-dips and for the previous Mars orbiter aerobraking missions.
- Sun-Velocity: spacecraft points towards the Sun. (S/C +Z-axis points to the Sun, +/-Y towards velocity direction.)
- Earth pointed: spacecraft points HGA to Earth for uplink/downlink. (S/C +Z-axis points to the Earth.)

The Fly-Y and Fly-Z orientations have constant spacecraft areas as seen by the drag pass. However the drag pass areas for the Sun-Velocity and Earth point directions will vary depending on the Earth and Sun geometries relative to Mars and the spacecraft orbit. The areas will vary between the minimal Fly-Y and maximal Fly-Z drag pass areas. Thus for simplicity, navigation error analyses assumed the worst case Fly-Z orientation. This also allows the verification of navigation requirements for all four possible periapsis orientations.

The required accuracy of the navigation predictions are linked to the required accuracy of spacecraft – and thus science instrument – pointing. The navigation error is just one source in the total spacecraft pointing error calculation. Working with the spacecraft team, an error allocation was assigned to navigation, in terms of orbital elements, which allowed navigation to meet its predict accuracy requirements in the contingency case of a missed uplink of an updated spacecraft ephemeris. This was folded back into the mission requirements as the capability to predict the orbital elements for 9.5 days in the nominal orbit and 2.8 days in the deep-dip orbit. Table 4 shows several representative analyses for the nominal orbit predict capabilities. Table 5 shows representative analyses for the deep-dip orbit predict capabilities. The column for the sixth orbital element, "time to periapsis", does not have a requirement listed. This is because the Periapse Timing Estimator, or PTE, controls this parameter on board the spacecraft to within 20 seconds. The numbers listed here show what the timing errors would be if PTE was not available. PTE will be described in the next section.

**Table 4: Nominal Orbit Prediction Capability, Orbital Elements (3σ)**

| Case | a [km] | e [] | i [deg] | Ω [deg] | ω [deg] | Period [s] | Time to Periapsis [s] | Out-of-Plane [km] |
|---|---|---|---|---|---|---|---|---|
| Requirement | 50 | 0.025 | 0.20 | 0.04 | 0.3 | | | |
| 1-Nov-2014 (5 days) | 3.9 | 0.0004 | 0.0034 | 0.005 | 0.04 | 14.4 | 67 | 0.36 |
| (9.5 days) | 13.0 | 0.0011 | 0.0094 | 0.014 | 0.14 | 48.0 | 213 | 0.43 |
| 26-Apr-2015 (5 days) | 4.0 | 0.0003 | 0.0170 | 0.013 | 0.04 | 14.6 | 71 | 2.39 |
| (9.5 days) | 13.6 | 0.0011 | 0.0190 | 0.013 | 0.13 | 49.9 | 240 | 2.39 |
| 25-Sep-2015 (5 days) | 6.7 | 0.0005 | 0.0383 | 0.016 | 0.04 | 23.0 | 73 | 6.44 |
| (9.5 days) | 21.1 | 0.0017 | 0.0402 | 0.016 | 0.14 | 77.5 | 246 | 6.44 |

**Table 5: Deep-Dip Orbit Prediction Capability, Orbital Elements (3σ)**

| Case | a [km] | e [] | i [deg] | Ω [deg] | ω [deg] | Period [s] | Time to periapsis [s] | Out-of-Plane [km] |
|---|---|---|---|---|---|---|---|---|
| Requirement | 50 | 0.025 | 0.20 | 0.04 | 0.3 | | | |
| 29-Dec-2014 (1.4 days) | 16.5 | 0.001 | 0.022 | 0.013 | 0.08 | 60.8 | 119 | 3.58 |
| (2.8 days) | 47.8 | 0.004 | 0.025 | 0.036 | 0.27 | 176.2 | 460 | 3.58 |
| 26-Aug-2015 (1.4 days) | 15.5 | 0.001 | 0.006 | 0.007 | 0.07 | 57.1 | 109 | 0.90 |
| (2.8 days) | 41.9 | 0.003 | 0.015 | 0.026 | 0.26 | 154.1 | 399 | 0.90 |

The other prediction accuracy requirement is to predict the timing uncertainty within the orbit to less than 20 seconds. This requirement is more difficult for navigation to meet, and drives the work schedule. Navigation has determined that it can meet the 20 second timing requirement within a 2.5 day prediction in the nominal orbit, but only within 3 periapses (~12 hours) in the deep-dip orbit. Figure 1 shows the predicted timing uncertainty over the entire primary science phase for a reference trajectory. The curves show the timing error for six lengths of prediction, ranging from 15 hours to 30 days. The five sharp peaks denote the deep-dip periods, where the spacecraft is lower in the atmosphere.

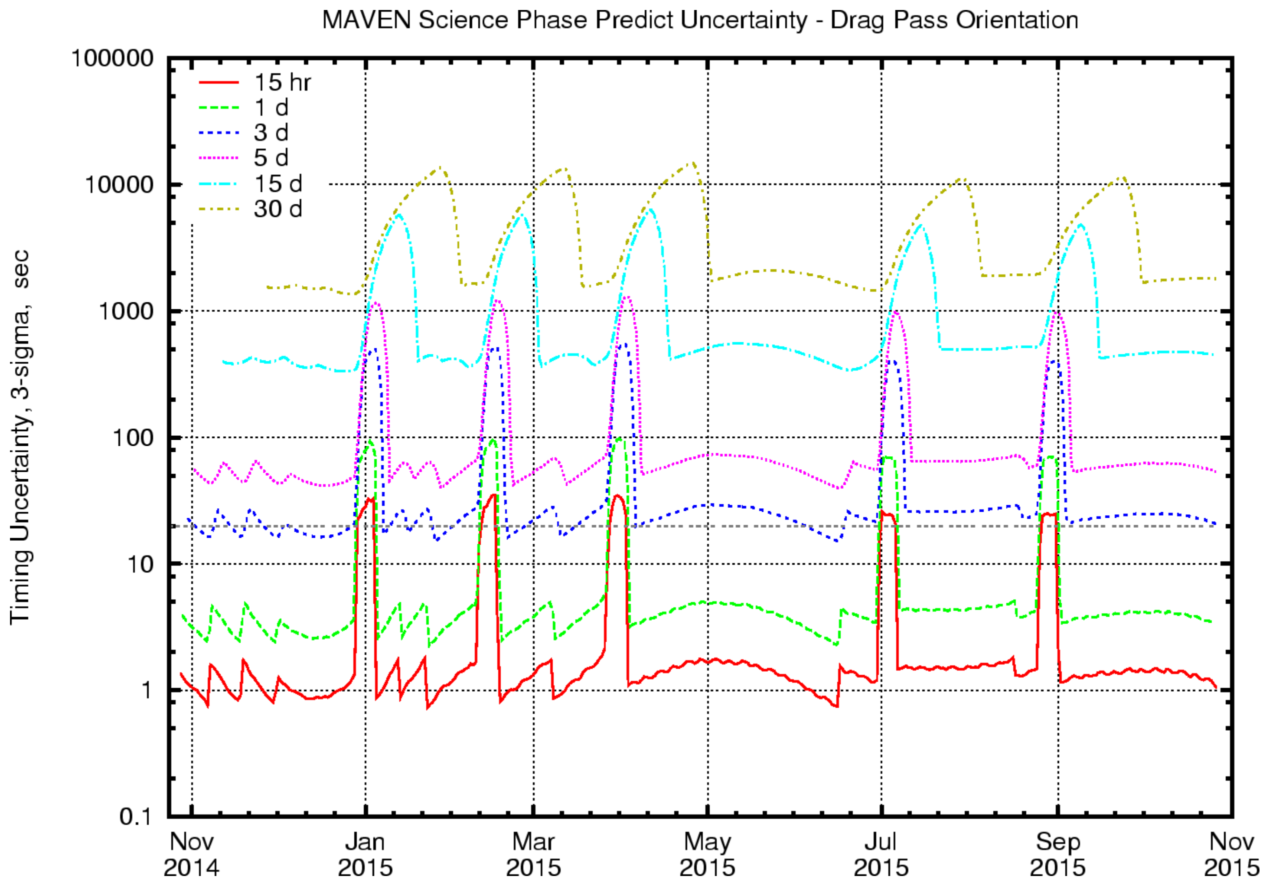


**Figure 2: Predict Timing Uncertainty**

### 3.4. Navigation Operations Schedule

The ability to meet the 20 second timing requirement drives much of the navigation operations schedule. Actually, the 20 second accuracy is required for a much longer period than navigation can provide. This is solved by having an enhanced version of the Lockheed Martin Periapse Timing Estimator (PTE) algorithm, used during MRO and ODY aerobraking, running on the spacecraft. Navigation just needs to deliver a predicted ephemeris that is accurate within 20 seconds through the upcoming HGA pass (Tuesday or Friday). PTE may be initialized with this uplinked ephemeris, after which it will automatically keep the on-board timing error within 20 seconds. Thus navigation will nominally plan to perform its analyses and predict delivery based on the LGA pass preceeding the HGA pass: that is, using the Monday or Thursday LGA pass. Navigation (NAV) is allocated a minimum of 5 hours in which to perform its analyses and deliver the predicted trajectory. The Spacecraft Team (SCT) is allocated a minimum of 7 hours to process the NAV predict, generate sequences, etc., and be ready to uplink to the spacecraft.

The 2.5 day 20 second navigation timing accuracy capability will allow some flexibility in the choice of the LGA pass. At least one if not both of the LGA passes on the previous day (Sunday or Wednesday, both with two DSN passes) may optionally be used, if needed, to resolve problems with DSN tracking data, simplify work schedules, and/or add extra padding into the scheduling of analyst work hours. In the worst case, the predict delivery can be skipped. PTE will keep the on-board timing accuracy within 20 seconds, and the 9.5 day predict capability for the other five orbital elements will allow navigation to still meet science pointing requirements. Figure 2 shows a simplified sample of the navigation weekly schedule.

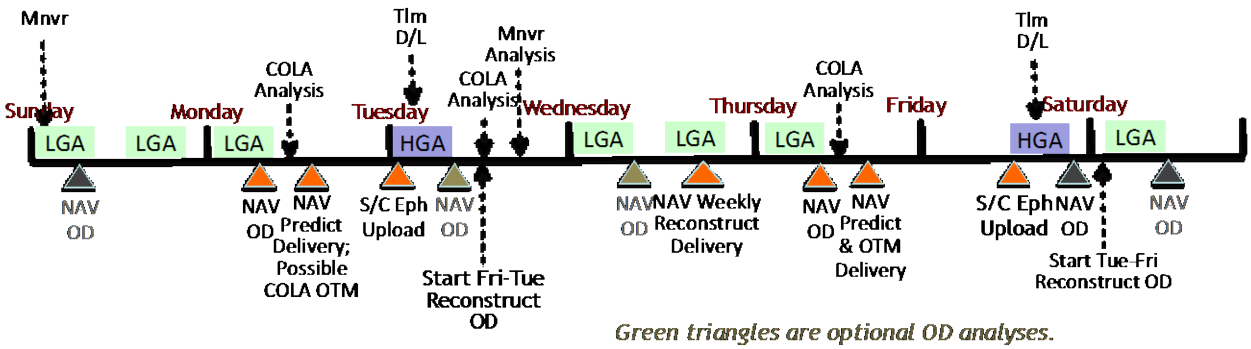


**Figure 3: Nominal Orbit Sample Weekly Navigation Schedule**

The deep-dip scenario is more demanding. It has continuous data, with the HGA pointed towards Earth for two of the orbits (HGA "passes"). The navigation predict must be delivered, processed and uploaded to the spacecraft via the HGA before the third periapsis after the periapsis in the navigation OD analysis arc. Navigation is allocated 5 hours for their process, and the SCT is allocated 6 hours. Taking into account light-times, upload times, etc., this does not leave any significant margin. The OD Doppler data arc cannot be arbitrarily chosen, since it is defined by the 3 periapsis 20 second prediction capability. If there are problems with the Doppler data arc, or problems in navigation or SCT processing, the fallback contingency is to skip the predict delivery and wait till the next day. PTE will keep the on-board timing within 20 seconds, and the navigation predict of the other five orbital elements will be good for one more day. Also note that there are two HGA "passes" per day. So, if necessary, a predict could be generated a half day later instead of one day. However that would require short term shifting of personnel work hours to off-nominal times, which is not desired. Figure 3 shows a simplified example of a deep-dip schedule.

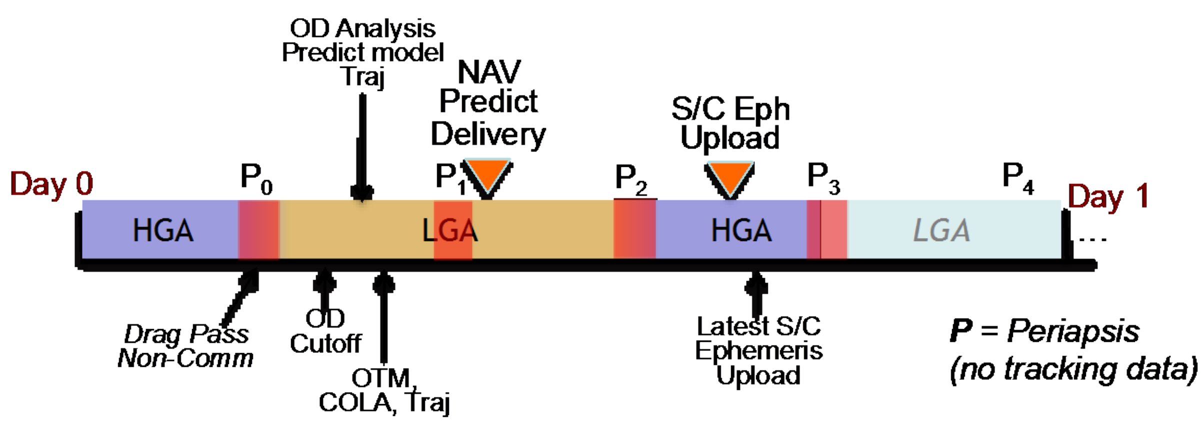


**Figure 4: Deep-Dip Orbit Sample Navigation Schedule**

The 5 hour allocation for the navigation analysis and predict delivery is significantly less than that allocated on previous Mars orbiter missions. It may include: orbit determination (OD), predict model generation, trajectory generation, Orbit Trim Maneuver (OTM) analysis, Collision Avoidance (COLA) analysis, final predict trajectory generation, and predict delivery to the project. A major reason for the ability to meet the 5 hour allocation is the streamlining and enhancing of the maneuver design process via Monte[3] scripts created by the navigation team. They have been tested in analyses and operations type scenarios with great success.

## 4. Maneuvers

### 4.1. OTMs and Corridor Control

Almost all maneuvers during the MAVEN science phase will be performed as Orbit Trim Maneuvers (OTMs). They include the following maneuvers. All of them will be executed at apoapsis, with the purpose of changing the periapsis altitude or orbit period.

- Corridor control maneuvers: to keep the maximum orbit density within the density corridor.
- Deep-dip walk-in and walk-out maneuvers: to transition to and from the nominal orbit and deep-dip orbit.
- Collision Avoidance (COLA) maneuvers: special quick maneuvers to avoid possible collisions with other spacecraft or bodies. (They are expected to be rare, if they occur at all.)

The OTM is a special maneuver process that allows quick execution of maneuvers. Since the science orbits have significant and uncertain atmospheric drag perturbations on every orbit, it is important to be able to quickly design and execute maneuvers to change the periapsis altitude in order to keep the spacecraft within the desired density corridor. For similar reasons, the OTM process was also used in MRO, ODY and MGS aerobraking. A maneuver design is composed of three parts, all of which are optimized for operations efficiency in the OTM maneuver process.

- *Magnitude*: The OTM $\Delta V$ magnitude is picked from a $\Delta V$ menu, delivered before launch. This allows the $\Delta V$ configuration files for upload to the spacecraft to all be pre-built and tested.
- *Epoch*: The OTM is always executed at apoapsis, as determined by PTE. Thus this "epoch" is always the same for every OTM. In addition, PTE will accurately know when apoapsis occurs. Using an absolute time epoch would be less efficient.
- *Direction*: There are only two choices for the OTM direction, allowing spacecraft configuration files to be pre-built.
    - *Up*: $\Delta V$ in velocity direction (increasing periapsis altitude)
    - *Down*: $\Delta V$ in anti-velocity direction (decreasing periapsis altitude)

Up to one corridor control OTM may be executed each week in the nominal orbit. Currently it is scheduled for Sunday morning, although it may be changed to Wednesday morning. The navigation Thursday predict analysis will determine if an OTM is required on Sunday. If so, the

[3] Monte is the core mission design and navigation software used by JPL/MAVEN navigation.

project will be notified, a decision will be made, and the OTM will be included in the Thursday predict delivery and uplinked on Friday to the spacecraft. During the deep-dips, an OTM may be performed as often as once a day. (However, this frequency is not expected in operations.) Thus for every predict delivery during the deep-dip, navigation will perform a maneuver analysis for a possible OTM. Typical corridor control OTM $\Delta V$'s for the nominal and deep-dip orbits are 1.4 m/s and 0.4 m/s, respectively.

### 4.2. Deep-Dip Walk-In and Walk-Out

The behavior of the atmosphere can change dramatically with a several kilometer change in altitude. Unfortunately there is little time allocated for navigation to maneuver in and out of the deep-dip, since that is a cost to science. The total deep-dip period is 8 days of continuous DSN coverage: 2 days to maneuver from the nominal to deep-dip orbit, 5 days of science, and 1 day to maneuver back to the nominal orbit. During the 2 days and 1 day of maneuvering the spacecraft will remain Earth pointed (except during the drag passes around periapsis).

During the walk-in, navigation must balance the need to quickly get into the deep-dip orbit, the uncertainty of the atmosphere due to large changes in altitude, and the safety requirement of not going above 7 $kg/km^3$ (mean density). The altitude change going from the nominal to deep-dip orbit is expected to be around 24-40 km. Based on the limited density altitude variation information from previous orbiters, the first walk-in maneuver could result in an error in the predicted density scale factor of 200% or slightly more. Taking into account all of this information, the first walk-in maneuver will target for a density $\leq 2$ $kg/km^3$. A sample $\Delta V$ magnitude for this maneuver is 3.8 m/s.

Since the deep-dip period only lasts for a total of 8 days, it is expected that the density behavior at the nominal orbit altitude should not have changed much. Thus only 1 day is allocated for getting back to the nominal orbit. The first walk-out maneuver will target a density of $>0.15$ $kg/km^3$.

### 4.3. Other Maneuvers

MAVEN has the requirement to stay in a 4.5 hour orbit. However, the drag passes during the science phase continually decrease the orbit period and apoapsis altitude. As a result, one or two Period Correction maneuvers (PCMs) may need to be performed during the science phase. They will be executed at periapsis, and will increase the period and apoapsis altitude. Technically it will be a fully designed maneuver. However, parts of the OTM process will be used to streamline the process. The PCM $\Delta V$ magnitude is expected to be around 16 m/s.

Other miscellaneous maneuvers might be performed during the science phase or after. They will also be fully designed maneuvers. For instance, at some point MAVEN will need to significantly increase its periapsis altitude in order to reduce the degradation of its orbit due to atmospheric drag.

Due to the multiple spacecraft orbiting Mars, there is a slight possibility of a collision between two orbiters (or other bodies, such as Mars moon Phobos). Per the established procedures of the

Mars Program Office and the current Mars orbiters, MAVEN navigation will track possible collisions with other bodies. If deemed necessary, MAVEN will execute a maneuver to prevent a possible collision. This process will not be discussed in detail here. It will be similar to the MRO and ODY COLA processes [9].

## 5. Summary

The MAVEN mission has a high degree of heritage from MRO. The science phase navigation process is similar to the MRO aerobraking process. However, the navigation accuracy requirements are much tighter than for MRO aerobraking. The reduced Doppler tracking data hinders the tracking of recent density behavior, thereby degrading predict capabilities. Nevertheless navigation has shown that it can meet all reconstruct and predict requirements, with contingency situations identified. The recent increase in DSN coverage significantly helps in contingency situations and in workforce scheduling. The OTM process is used for almost all science phase maneuvers, allowing rapid turn around in the maneuver design and execution. The OTM $\Delta V$ menu is expanded to allow it to also be used for maneuvering to and from the deep-dip orbit. The eight day deep-dips will be the most intensive part of the science phase.

## 6. Acknowledgements

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