MAVEN Navigation During the First Mars Year of the Science Mission

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The Mars Atmosphere and Volatile Evolution mission (MAVEN) is the first mission devoted to studying the Martian atmosphere. From a Navigation perspective it is unique in that science is performed at near aerobraking altitudes. This results in the requirements on Navigation trajectory accuracy requirements which are an order of magnitude tighter than those of aerobraking phases on previous missions. Navigation experiences with the Mars atmosphere are described as they pertain to Navigation models, trajectory reconstructions, trajectory predictions, density corridor control, and collision avoidance of other bodies around Mars.

I. Introduction

The Mars Atmosphere and Volatile Evolution mission (MAVEN) is unique in that it carries a suite of experiments with the sole purpose of a detailed study of the Martian atmosphere.[1] To accomplish this, MAVEN has an eccentric science orbit with a periapsis altitude of around 150 km and an apoapsis altitude near 6200 km. The orbit is at an inclination of 74 degrees. This orbit allows periapsis to naturally progress over the planet, covering all local solar times and most latitudes. The nominal mission is designed to keep the spacecraft within an average density corridor of 0.05-0.15 kg/km^3. Orbit Trim Maneuvers (OTMs) are chosen up to once a week to keep the spacecraft within this corridor. The variation in the Mars atmosphere has resulted in the periapsis altitude varying between 130 and 180 km. Periodically, "deep dips" are performed where the spacecraft is maneuvered to fly in a much deeper 2.0-3.5 kg/km^3 density corridor for five days. The periapsis altitudes for these deep dips have varied between 119 and 145 km. OTMs may occur as frequently as once per day during this time.

This paper will describe the Navigation experiences during the first Mars year of MAVEN science (November 2014 – August 2016). The Navigation requirements and responsibilities will be discussed. Then the atmosphere behavior will be examined, along with its effects on corridor control. This will lead to a discussion of trajectory

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reconstruction and prediction accuracies, and a comparison to the original project requirements. Finally there will be a brief discussion on the specialized prediction related topics of collision avoidance and Mars lander relay planning.

II. MAVEN Science Mission

After arriving at Mars on September 22nd, 2014, MAVEN's science phase began on November 16th, 2014, and its extended science phase began on November 16th, 2015. During these periods, MAVEN's primary purpose is to take measurements that can help answer fundamental questions about Mars's atmosphere. The three main science objectives of the MAVEN mission are to determine the structure of Mars's upper atmosphere; to study the interaction between the sun and Mars's upper atmosphere; and to determine the rates of loss of Mars's upper atmospheric gases to space. This final objective allows MAVEN's science team to extrapolate atmospheric conditions back in time so that the atmosphere of ancient Mars can be better understood. Though extrapolation should always be performed with caution, this calculation is crucial to the understanding of the habitability of ancient Mars since it is postulated that the loss of gas to space is a significant driver of Martian climate change, and since it is known that Mars's surface was once warmer and wetter than it is today.[1]

To take the measurements necessary to fulfill MAVEN's scientific objectives, the spacecraft carries eight instruments that assess the energetic inputs to the upper atmosphere from the sun, and how the upper atmosphere responds to those inputs. Some instruments acquire in-situ atmospheric measurements while others observe Mars's atmosphere remotely. To facilitate both types of instruments, MAVEN's orbit was designed with a low periapsis altitude (< 200 km) and a high apoapsis altitude (> 6000 km). The periapsis altitude is determined by targeting a particular range of atmospheric density at periapsis. The apoapsis altitude was chosen so that it was high enough for quasi-global observations but low enough that the orbital evolution driven by the non-spherical Mars would move pericentron through a range of Martian latitudes and local solar times.[2]

III. Spacecraft

MAVEN is a three-axis stabilized spacecraft with fixed solar panels. For telecommunications, MAVEN is equipped with a non-articulating high-gain antenna (HGA) and two low-gain antennas (LGA) (Figure 1). During nominal science operations in Mars orbit, the HGA is used for communicating with Earth twice weekly for commanding, and telemetry and data download, while daily LGA passes are used primarily to collect tracking data. MAVEN's body-fixed axes are shown in Figure 1. The X axis is positive along MAVEN's articulated payload platform; the Z axis is positive along the HGA boresight; and the Y axis is parallel to the long axis of MAVEN's solar panels, consistent with a right-handed coordinate system. The forward LGA is canted 22 degrees from the +Z axis towards the -X axis. The aft LGA is canted 22 degrees from the –Z-axis towards the +X-axis. The two outer solar panels are canted 20 deg towards +Z for aero-pass stability.

Because the eight onboard spacecraft instruments each measure different physical parameters and have different goals, the instruments prefer different spacecraft orientations. To resolve these conflicts, MAVEN assumes different orientations during different segments of its orbit at Mars. Each orbit is divided into pre-defined regions as shown in Figure 2. There are ten sets of two-orbit configurations or "scenarios" for the nominal science orbits. The two-orbit configuration is repeated over an one week onboard spacecraft sequence. Table 1 describes the spacecraft orientations at periapsis

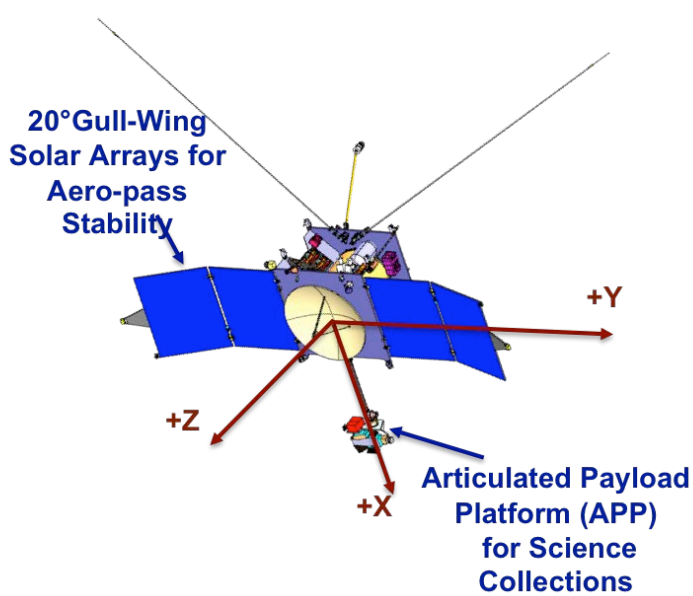

Figure 1. MAVEN spacecraft and body-fixed coordinate system.

for these scenarios. The "Fly-Z" and "deep dip" orientations are practically the same, and may often be used interchangeably in the discussions below. The aero-stabilized drag pass is the only periapsis orientation used during deep dips.

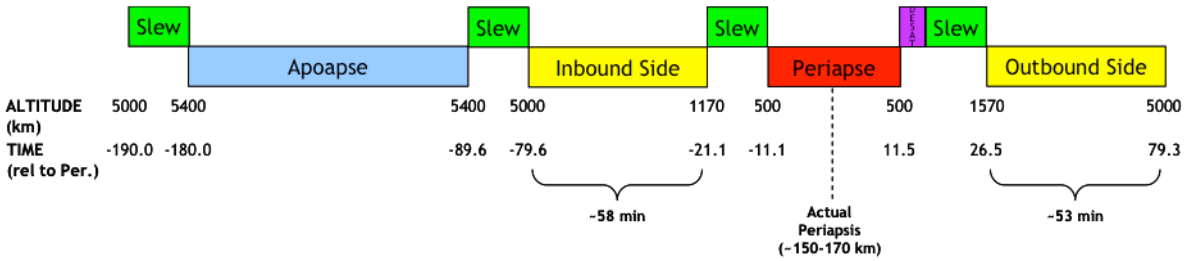

Figure 2. Segmented science orbit timeline.

Table 1. Attitude mode definitions.

ACS Mode	Science Mode	Definition
Velocity-Nadir	Fly-Y	+/-Y in velocity direction. +X towards nadir.
	Fly-Z	-Z in velocity direction. +X towards nadir (clocked +12 deg off-nadir). (Similar to drag pass.)
Sun-Velocity	Sun-Velocity	+Z to Sun. +/-Y towards velocity direction.
Earth Point	HGA Comm	+Z to Earth.
Drag Pass	Deep Dip	-Z in velocity direction. +X towards nadir. (Aero-stabilized)

IV. Navigation Responsibilities

The altitudes for both the MAVEN nominal and deep dip orbits are not much higher than a typical aerobraking altitude.* However the purpose of the aerobraking phases on previous missions was for trajectory modification, whereas MAVEN's purpose is science. Thus, MAVEN Navigation was required to achieve a 20 second timing accuracy, an order of magnitude smaller than the 225 second requirement levied on the previous aerobraking missions. With the significantly reduced tracking data and varying spacecraft orientations needed for science observations, the MAVEN mapping mission has unique challenges compared to aerobraking.[2,3]

The Navigation Team is responsible for generating predicted trajectories, reconstructed trajectories, and recommending OTMs to keep MAVEN in the density corridor. Reconstructed trajectories are needed by the science teams for processing their data. It is also needed by Navigation to derive reconstructed densities. These densities are used to create an accurate density model for the predicted trajectories, and to determine the need for and size of OTMs to keep MAVEN within the density corridor. The predicted trajectories are used for the generation of spacecraft onboard ephemerides, spacecraft sequence generation, and the design, placement and sequences for future science observations. They are also critical to ensure that MAVEN does not collide with any other bodies around Mars. The current collision avoidance (COLA) analyses only involve the active spacecraft around Mars and its moon Phobos. The predicted trajectories are also used for MAVEN relay support of Mars landed assets, although so far such support has been minimal.

The following are the major requirements levied on Navigation by the project during the science phase of the mission.

- The nominal MAVEN science orbit shall be an elliptical orbit, with an inclination of 75 +/-1.875 degrees, and a period of 4.5 +/- 0.11 hours, targeted to a periapsis density corridor of 0.05 to 0.15 kg/km^3.
- MOS/GDS shall predict the periapsis uncertainty to less than 20 seconds of periapsis passage time for the first orbit of each new mapping ephemeris loaded on-board.

* They are similar to Mars Global Surveyor's light aerobraking altitude.[5,6]

- The Nav system shall predict the MAVEN orbit and spacecraft position to within the following accuracies (3-sigma) for at least 9.5 days from the orbit determination cutoff time during nominal science and relay orbits:
    - 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
- The Nav system shall predict the MAVEN orbit and spacecraft position to within the following accuracies (3-sigma) for at least 2.8 days from the orbit determination cutoff time during deep dip orbits:
    - 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
- Positional knowledge of the orbiter shall be reconstructed to within 3 km (3-sigma, 3D), excluding DSN tracking gaps and atmospheric blooming events.

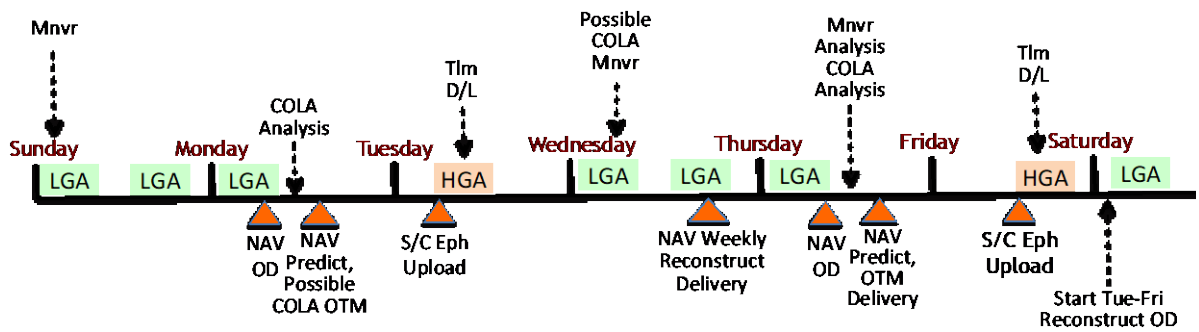

Figure 3. Navigation weekly timeline in the nominal orbit.

The nominal science orbit has a weekly operations cadence as shown in Figure 3. There is approximately one DSN tracking pass per day. Navigation can use tracking passes on the LGA, which do not affect science. The Tuesday and Friday "communication" passes require rotating the spacecraft to point the HGA to Earth, thus losing science observations. Navigation is responsible for delivering updated trajectory predictions twice per week, on Monday and Thursday morning. Current orbit determination, COLA analysis, corridor control analysis, and an official project OTM decision are all incorporated into the prediction delivery. A predict is used to update the onboard MAVEN ephemeris and related files during the HGA communications pass on the following day. An OTM, if required, is typically executed early on Sunday, although MAVEN has the capability to execute it at any apoapsis. On Wednesday Navigation delivers a reconstruction of the MAVEN trajectory over the preceding week.

The deep dip has a daily cadence as shown in Figure 4. The Navigation work performed during a week of nominal orbit operations is compressed into a single day of deep dip operations. This daily cadence is due to the low altitudes and large atmospheric densities encountered by the spacecraft, which greatly reduces Navigations capabilities to maintain down-track timing requirements. This timeline is similar to those used on other aerobraking missions, as is the continuous DSN coverage. Navigation delivers an updated prediction and reconstruction daily, along with supporting daily OTM opportunities. Both the Navigation and Spacecraft Team nominal orbit timelines were reduced in order to fit into one day the orbit determination, COLA analysis, corridor control analysis, OTM decision, spacecraft uploads (and downloads), and OTM execution. Note that a day is a little over five orbits (~22.5 hours). Therefore Navigation nominally has only three density estimates (P1, P2, P3 after maneuver on A0) from which to derive the current average density relative to the corridor, which is then used in making an OTM decision (A5). After the execution of a maneuver at A5 (if needed), the entire daily sequence is repeated. Since five orbits is not quite a day, periodically there will be a six orbit "day". In the later deep dips Navigation was able to use four density estimates during the six orbit days to determine the average density and upcoming OTM.

The SCT has less than two orbits to generate and upload a new spacecraft ephemeris, upload OTM products, upload any necessary spacecraft or science related sequences, and verify that the spacecraft received the uploads. The SCT also needs to work around the drag passes – during which the spacecraft is not Earth pointed, but in an

aero stable "deep dip" orientation – and any Earth occultation periods. Station handovers must also be avoided. Since the MAVEN predictions are relatively poor due to atmosphere perturbations, one cannot schedule the work timeline for a deep dip well in advance. At most, one can put together a draft schedule a month in advance, and then tweak the schedule as one gets closer to the deep dip. One has to work around the DSN schedule for MAVEN, since that would have been finalized long before. So continuous tracking and long DSN passes are very beneficial.

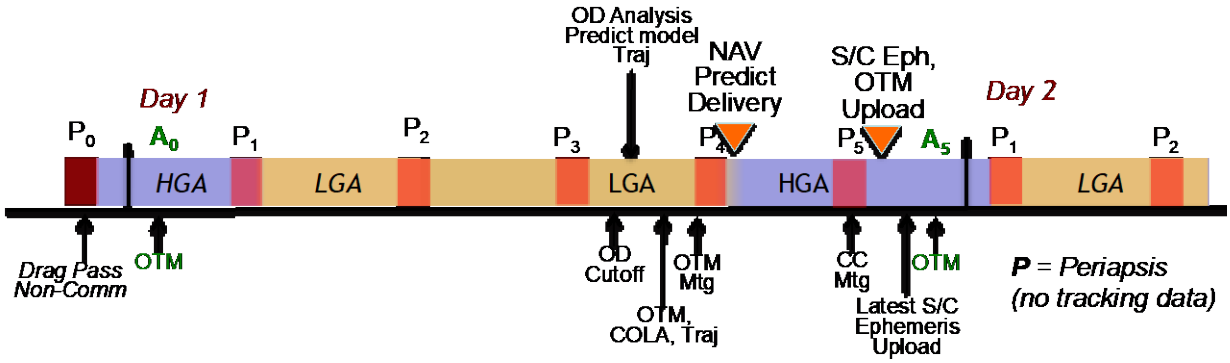

Figure 4. Navigation daily timeline in the deep dip orbit.

V. Maneuvers

It was decided to cancel the Trajectory Correction Maneuvers (TCMs) 3 and 4 during cruise. This resulted in the post Mars insertion inclination being 74.2 degrees, which was within the requirement. The orbit inclination remains stable, so no additional maneuvers are required to maintain the inclination requirement.

The main type of maneuver during the science phase is the Orbit Trim Maneuver (OTM). This maneuver is executed at apoapsis, in the positive or negative spacecraft velocity direction, and with a ΔV magnitude predefined in Table 2. This predefined "epoch", direction and ΔV magnitude allows the maneuver process to be greatly streamlined for both the Navigation and Spacecraft Teams. This is the same process as was used during the aerobraking phases of the previous NASA Mars missions.[5-8] OTMs are used to keep MAVEN within the density corridors (including walking into and out of the deep dip), and to avoid potential collisions with other spacecraft and Phobos. The project decision on an OTM is made near the end of the preceding prediction analysis. Navigation includes the project OTM decision in the final predict trajectory before delivery to the project. (See Figures 3 and 4 above.)

Due to the low periapsis altitude, the orbit period and apoapsis altitude are constantly decreasing. As a result a Period Correction Maneuver (PCM) needs to be periodically executed. A PCM is required about once a year, or after three deep dips. The PCM is a manually designed and large "pitch-over" maneuver. Each PCM is executed at periapsis in the velocity direction, targeting a period near the maximum allowed value of 4.61 hours. The ~15 minute burns, centered on the nominal periapsis epoch, start from a velocity pointed attitude and pitch over about

Table 2. Science phase OTM ΔV Menu

ΔV #	Magnitude (m/s)	Periapsis Altitude Change (km, approx)
1	0.2	1.3
2	0.4	2.5
3	0.6	3.8
4	0.9	5.7
5	1.2	7.6
6	1.5	9.5
7	1.8	11.3
8	2.1	13.2
9	2.4	15.1
10	2.7	17.0
11	3.0	18.9
12	3.3	20.8
13	3.6	22.7
14	3.9	24.6
15	4.2	26.5
16	4.5	28.4
17	4.8	30.2
18	5.1	32.1
19	5.4	34.0
20	5.7	35.9
21	6.0	37.8

the orbit normal vector at a constant rate designed to maintain velocity point and improve efficiency. A 31 m/s PCM-1 was executed on 12 Aug 2015. A 32.26 m/s PCM-2 is planned to be executed on 17 Aug 2016.

VI. Navigation Models

Navigation uses JPL's Mission Design and Navigation Toolkit Environment (MONTE)[9] for high-precision simulations. During MAVEN's science phase, the dynamic model includes gravity from the sun, the planets, Phobos, Deimos, and Pluto, with states retrieved from the DE430 and MAR097 ephemerides. 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, and thruster firings.

Navigation models Mars's atmosphere with the 2005 Mars Global Reference Atmospheric Model or Mars-GRAM (MG),[10] which relies on various atmospheric parameters output by the NASA Ames Mars General Circulation Model (MGCM) and the University of Arizona Mars Thermospheric General Circulation Model (MTGCM). These models are physically based and cover the entire planet. MGCM provides data tables below 80 km altitude; MTGCM provides the tables between 80 and 170 km altitude. Above 170 km, MG uses information from a modified Stewart thermospheric model. Mars-GRAM has three "MapYear" modes. Navigation started using MapYear 1 (MY1), but quickly changed to MapYear 0 (MY0). In the discussions below, if the MapYear is not explicitly mentioned, it is assumed to be MY0. Roughly speaking, one can think of the MapYears as follows. (See reference x for more detailed information.)

- MapYear 0 is a "general" or "average" atmosphere model.
- MapYear 1 is based on the first Mars year of data from the Mars Global Surveyor (MGS) Thermal Emission Spectrometer (TES).
- MapYear 2 is based on the second Mars year of data from the MGS TES.

Details of the orbit determination analysis used to fit the 2-way Doppler data and reconstruct the MAVEN trajectory are given in references 2 and 3. The trajectory prediction accuracy is driven by the predicted density accuracy assumptions. Navigation assumes there is a 40% bias and a 105% orbit to orbit (or "white noise") 3-sigma uncertainty. The 105% uncertainty is similar to that used for the previous NASA Mars orbiters. However these orbiters used a 30% bias uncertainty. Due to MAVEN having less tracking data than the other orbiters during the primary mission, and the larger MAVEN orbit period, MAVEN has fewer quality reconstructed densities from which to derive a nominal density. This is especially true during the deep dip, where MAVEN may only have three density points with which to determine an average. For these reasons, and due to the uncertainty and difficulty in modeling the varying spacecraft periapsis orientations, MAVEN increased its 3-sigma density bias error to 40%.

VII. Atmospheric Density and Corridor Control

The main error sources for Navigation are the Mars atmospheric density and the non-deterministic OTM schedule. However, the OTMs are driven by the density behavior, so being able to reconstruct and predict the density is of great importance for Navigation. Navigation uses its reconstructed densities, along with the Navigation atmosphere model, Mar-GRAM Map Year 0 (MG MY0), plus information from the Atmosphere Advisory Group (AAG),[*] to predict the future density behavior. The accuracy of this prediction depends on the accuracy of the Navigation reconstructed densities, the near-term trends in the density, the consistency with the MG MY0 model, the expected frequency of the upcoming OTM's, the Mars season, and the actual behavior of the atmosphere in the following weeks.

MG is a complex model composed of various equations and tables that apply to different parts of the atmosphere, making it difficult to directly estimate the model parameters using only two-way doppler data from the limited region of the atmosphere near periapsis. Instead, Navigation estimates a scale factor on the density computed by MG, typically estimating an independent value at each periapsis. Thus the shape of the MG density curve (and thus the effective density scale height) is not changed. Rather the MG curve is scaled up or down by this estimated factor to give the total drag pass ΔV effect (or orbit period change) derived from the Doppler. The actual density profile around periapsis can be very different from a Gaussian or centroid shape similar to the MG model. It is not

[*] The AAG is composed of lead Mars atmosphere scientists Richard Zurek and Stephen Bougher, along with key players from instruments which have information on the current behavior of Mars: Mars Reconnaissance Orbiter (MRO) Mars Climate Sounder (David Kass), MRO Mars Color Imager (Bruce Cantor), Mars Odyssey (ODY) Thermal Emission Imaging System (Mike Smith), MAVEN Accelerometer Team (Robert Tolson, Darren Baird, Rafael Lugo), and Navigation. The AAG meets once a week while in the nominal science orbit to discuss the current atmosphere behavior. The AAG meets once a day during the deep dips.

that unusual to observe in the spacecraft accelerometer data two distinct maximum density peaks around periapsis or other strange profiles. Also, if one fits a centroid to the actual density profile, the time of the centroid peak (along with the actual density peak(s)) relative to periapsis may be significantly different from the periapsis offset modeled in MG. This centroid peak can be off from periapsis by a minute or more, but is usually offset on the order of tens of seconds. This time can also vary significantly from orbit to orbit. The average time offset from periapsis can be a function of the season on Mars, the periapsis latitude, and dust storms. There have been several periods where the actual density peaks have been on the opposite side of periapsis from the MG model. The different MG Map Year models sometimes have similar discrepancies with each other.

Roughly speaking, the Mars density can be thought of as a combination of two cyclical curves: the 687 day Mars year and the 11 year solar cycle. The atmospheric density and volatility increases as Mars approaches its perihelion,[*] whereas the atmosphere is quiet around Mars apehelion. The 11 year sinusoidal solar cycle curve ends up shifting this Mars yearly sinusoidal density curve up or down.[†] This simple conception of the atmosphere behavior worked well for the previous NASA Mars orbiters (MGS, ODY, MRO) since their periapses were fixed near the south pole. Near perihelion Mars is at its southern summer, resulting in large density increases being seen by these orbiters. In the north it is "winter". However this density behavior near perihelion prevents the densities from dropping significantly in the north during its winter, plus the atmosphere volatility during this season is observed in both the south and north.

To be more exact, Mars perihelion (12 Dec 2014, 29 Oct 2016, 16 Sep 2018) occurs at solar longitude (Ls) = 251 degrees with southern summer solstice at Ls = 270 degrees. Mars apehelion occurs at Ls = 71 degrees with northern summer solstice (southern winter) at Ls = 90 degrees. Although significant dust storms can occur during an extended period around southern summer, they are most likely to occur during the months after perihelion.

[*] The maximum is actually centered a little past perihelion.

[†] Unfortunately, the recent solar cycle maximum was one of the lowest on record, resulting in significantly lower densities than MAVEN was hoping for during its primary mission science campaign.

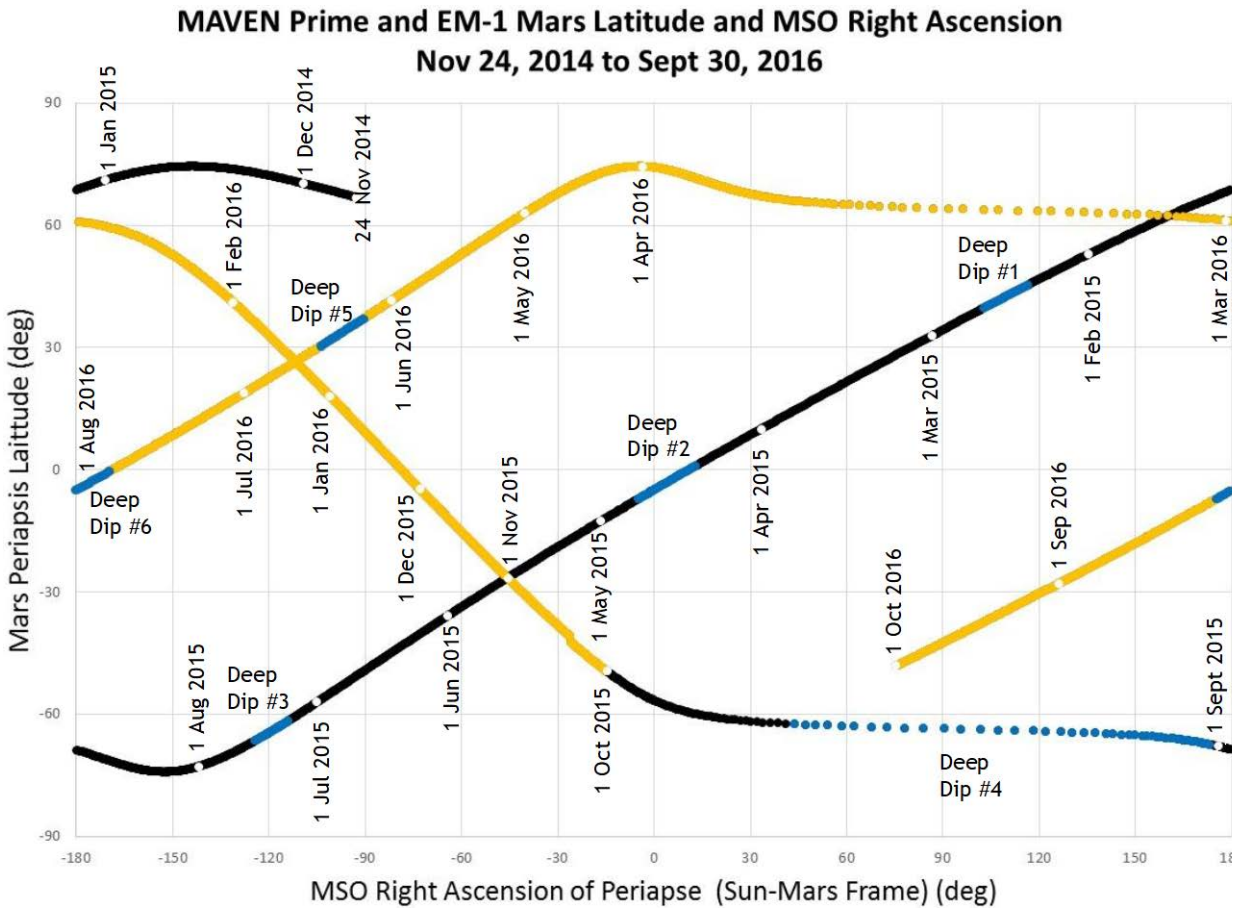

Figure 5. MAVEN periapsis latitude and Mars Mean Equator right ascension: 24 Nov 2014 to 30 Sep 2016

MAVEN's 74 degree inclination allows its orbit to precess over all local times and latitudes between ±74 degrees. However MAVEN will not necessarily cover the same part of the planet during the same Mars season. For example, MAVEN oscillates every Mars year between Mars perihelion occurring in the northern or southern hemisphere. The MAVEN periapsis ground track walk over the planet is shown in Figure 5, along with the locations of the deep dips. (The X-axis is defined as the dihedral angle, about the Mars orbit normal vector, from the Sun vector to the periapsis vector.) MAVEN inserted into a Mars orbit on September 22, 2014 (UTC). By October 6 (after Periapsis Lowering Maneuver #2) MAVEN had maneuvered near to the nominal science orbit. The primary science phase officially started on November 15, near perihelion and the volatile atmosphere season. When perihelion occurs again in October 2016 MAVEN will be in the southern hemisphere.

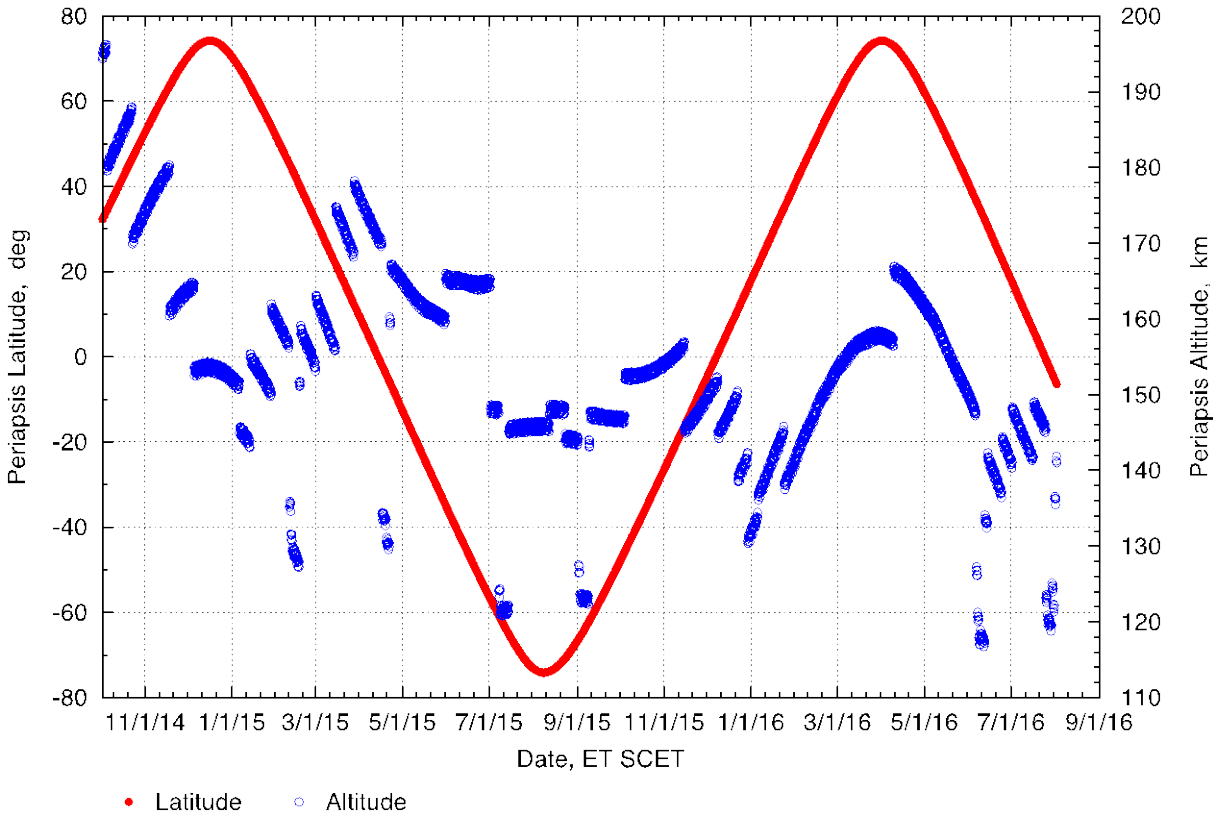

Figure 6. MAVEN latitude and periapsis altitude.

MAVEN does not directly see how the density changes near a constant altitude. Rather MAVEN tries to stay in its density corridor by changing its altitude. Figure 6 shows a plot of the latitude and periapsis altitude during the Mars science phase. The altitude changes via OTM's required to keep MAVEN in the corridor are obvious in this plot. One can also see the natural oscillation of the periapsis altitude due to gravitational effects and the flattened ellipsoidal shape of Mars. The altitude increases as MAVEN goes from the middle latitudes up towards the north pole. The altitude starts to level off as one gets deeper into the southern latitudes. The science phase started during southern summer, and will get back into southern summer in the latter part of 2016. MAVEN was in the north during the first southern summer, but will be in the south during the second one. Although MAVEN did not see the full effect of the high densities in 2014 since it was in the north, it still encountered increased atmosphere volatility during this season. In other words, MAVEN started its science campaign during the most difficult season of Mars. The higher periapsis altitudes near the beginning of the science phase were mostly due to being at the end of the 11 year solar cycle maximum.

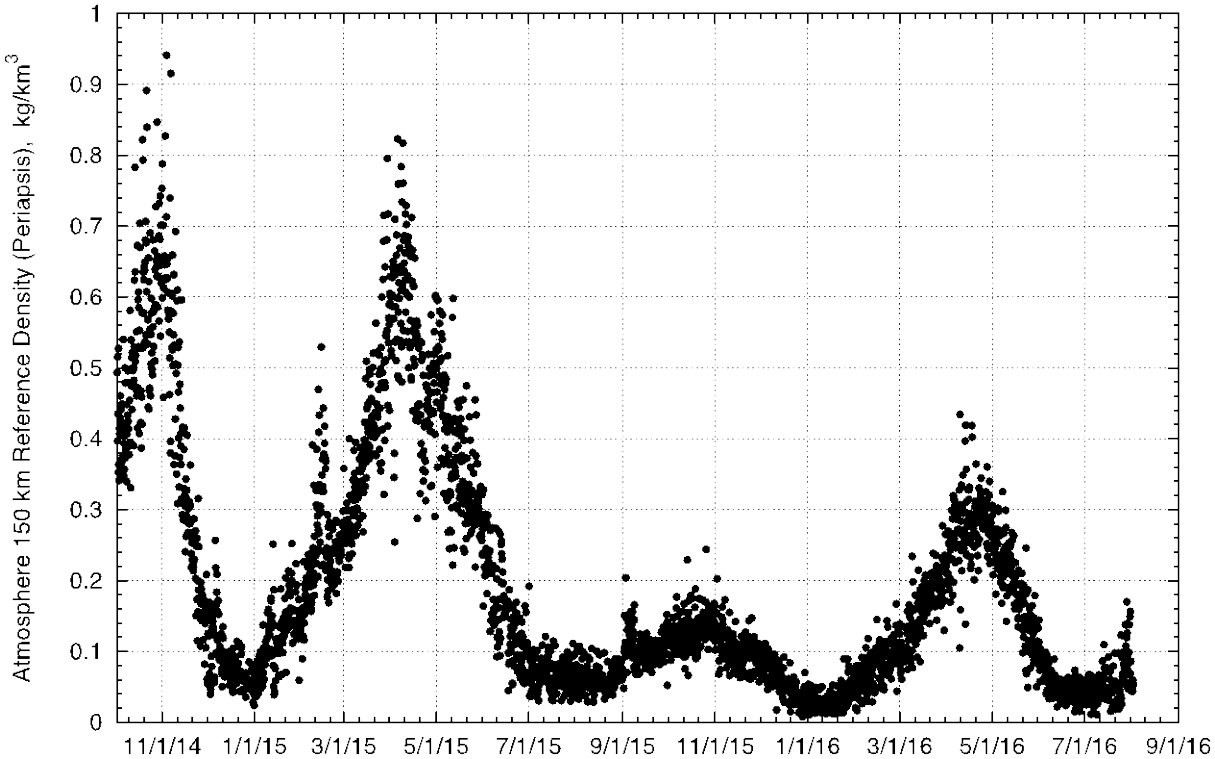

Figure 7. MAVEN periapsis density mapped to a constant 150 km periapsis altitude.

It is also instructive to look at the density behavior at a constant altitude. Figure 7 takes the Navigation estimated densities in Figure 8, and maps them to a constant 150 km altitude via the MG atmosphere model. Figure 7 shows three local density maxima at November 2014, April 2015, and April 2016. Even though this density plot has been simplified by removing the dependency on altitude, it is still a function of latitude, Mars season, and the solar cycle. The actual density behavior, shown in Figure 8, is a function of the periapsis altitude trend and the density trend at a fixed altitude. Some interesting atmosphere information might be able to be derived from Figures 6-8 with a more detailed examination.

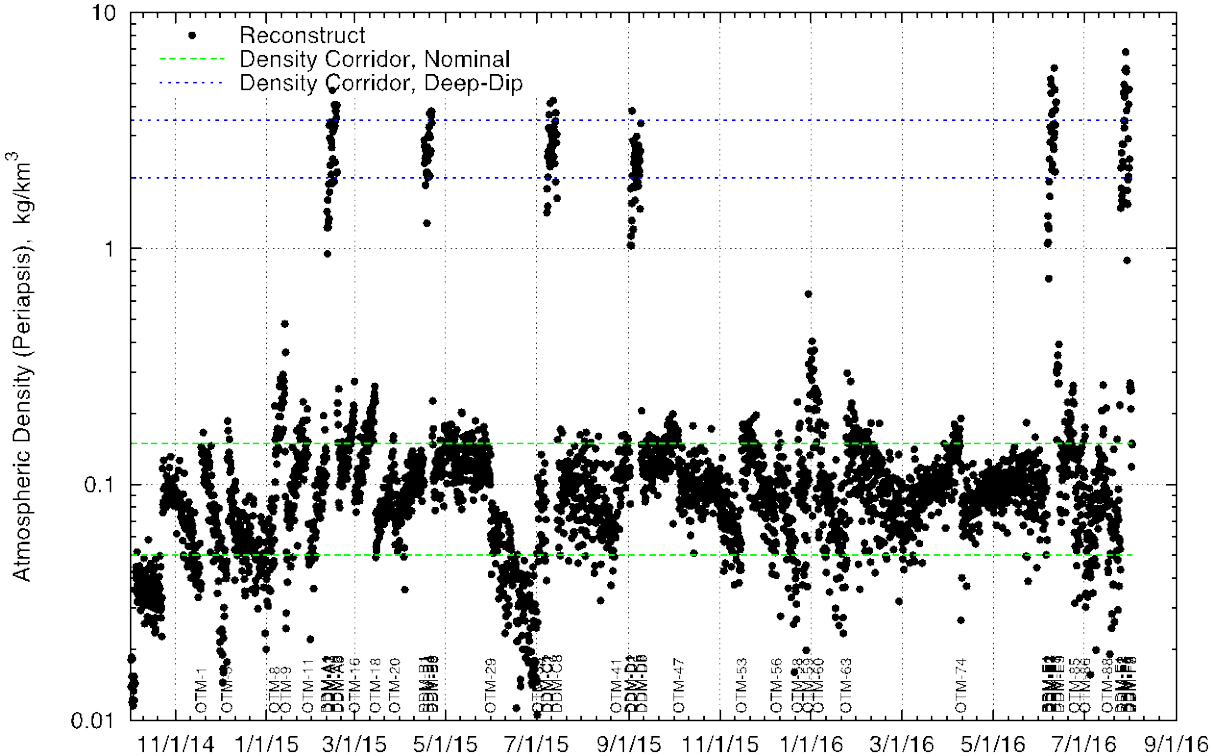

Figure 8. Periapsis density in the nominal science orbit.

A. Nominal Science Orbit

The first few months of the science phase were one of the most challenging periods in the nominal science orbit for Navigation. Despite these challenges, except for short periods of small densities at the beginning of December and high densities in early January, the project was able to successfully keep MAVEN in the density corridor. Figure 8 shows that there were significant downward trends in the density till December 2014, followed by significant upward trends for the first three months of 2015. Therefore OTM's were needed more frequently than during most other times in the mission. Another complication was the large inconsistency between the atmosphere model MAVEN was using and the actual density behavior that was observed. Before MAVEN was launched it was agreed that Mars-GRAM 2005 Map Year 1 (MG MY1) would be used. Figure 9 shows that this model worked well during most of the transition phase from Mars Orbit Insertion to the science phase. One can see that the Navigation scale factor estimates on the MG MY1 density model remained constant. However towards the end of the transition phase, as Navigation was refining the orbit for the start of science, this model started to behave poorly. In early November, the estimated density scale factor on MG MY1 started rapidly decreasing from 3.0 to 0.2. MY1 was predicting a constant density during the first week of November, followed by a significant increasing trend peaking around November 25, followed by a decreasing trend. MY0 was predicting a significant downward trend which nearly leveled off in December. (The MY2 trend was in between these two trends.) Thus at the start of nominal science MY1 was implying that an "up" OTM was needed to go to higher altitudes, whereas MY0 was implying that a "down" OTM was needed to go to lower altitudes. After a few weeks it was determined that the density trend was much closer to the MY0 prediction. It appeared that there was a dust storm at this season during the first year of MGS TES measurements, resulting in the significantly different MY1 trend. It seemed preferable to have a more general or "average" density model for MAVEN Navigation operational use. Otherwise one would need to determine what (if any) specific events, such as dust storms, occurred during the MGS TES Mars year 1, subtract out those effects, then add in any special atmosphere activity that MAVEN was currently seeing. Thus Navigation switched to MY0 on 15 December 2014, and has used it ever since. Navigation also refined their process to look at all MapYear predictions for OTM decisions.

Figure 7 shows that at the beginning of 2015 the density (at a 150 km altitude) makes a sharp change from decreasing to increasing. MG MY0 also predicted this increasing density trend, but MY1 and MY2 did not. The

Navigation reconstructed densities showed no evidence for this trend, although the last few days had some large variation in the density estimates. Since MAVEN had just gone out of the corridor due to the recent decreasing density trend, a 0.9 m/s OTM-08 was executed to move MAVEN down in altitude by 5.5 km. However by the time OTM-08 executed the density had started exhibiting a large increasing trend. Thus the density quickly went out of the corridor.

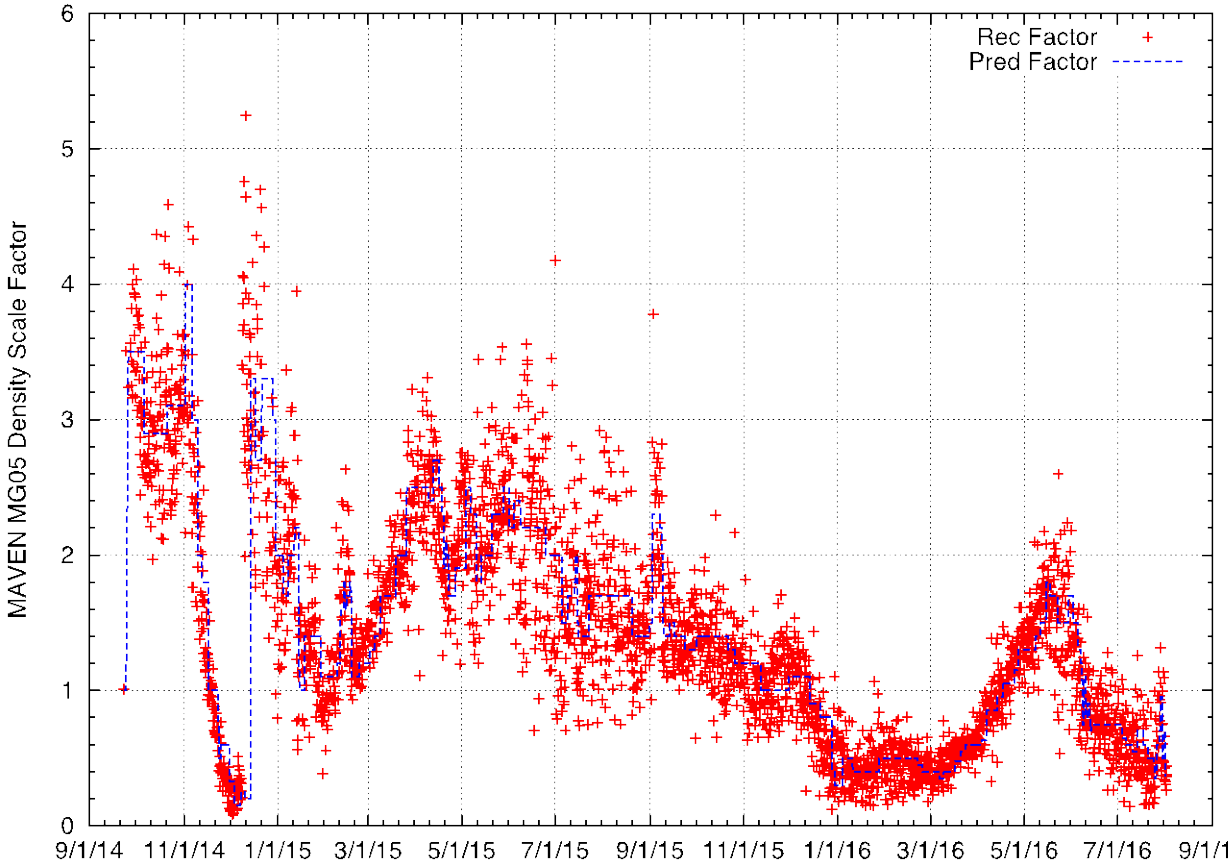

Figure 9. Navigation estimated scale factor on Mars-GRAM 2005 model.

From April to June of 2015 the density stayed fairly flat. Only one OTM was required (except for deep dip 2). Figure 7 shows that the density at 150 km decreased during this time. However the altitude was also naturally decreasing. Both effects cancelled each other out so that the net effect was little density change, resulting in MAVEN staying in the nominal density corridor with minimal OTMs. A similar situation occurred from February to June or 2016. During that time MAVEN was able to go for eleven weeks without an OTM. This illustrates the fact that one is not only looking at the atmosphere and its predicted behavior, but also at any changing altitude. This can be from the natural progression of the radial distance from the center of Mars for that specific orbit and/or altitude changes due to the oblate shape of Mars and periapsis latitude progression.

Solar conjunction with its command moratorium (including OTMs) occurred in June. The last maneuver opportunity before solar conjunction was OTM-29 on May 31. The first OTM opportunity after solar conjunction was OTM-33 on June 28. Even though it was predicted that the density would decrease during that time, the project decided to be safe and execute OTM-29 to bring the density to a low value – but still in the corridor. During solar conjunction the density did decrease, and a 2.7 m/s (16.8 km altitude decrease) OTM-33 was executed on July 2 (postponed from June 28) to bring the density back into the corridor.

During the 2015 Christmas and New Years time period, when many people were on vacation and traveling, there was an unexpected behavior in the density. MG (MY0) had been displaying a downward density trend, requiring OTM's approximately every two weeks. At the OTM-58 decision meeting on December 21 everything looked consistent with the previous few weeks trends. Because of this consistency, and the fact that many people would be

on vacation for the next two weeks, it was decided to decrease the periapsis altitude by 11.3 km by performing a 1.8 m/s "down" OTM-58 on December 22. It was expected that this maneuver would put MAVEN at the upper density corridor limit of 0.15 kg/km^3 or slightly above. However the density started decreasing much faster than MG predicted. As a result a 1.8 m/s "down" OTM-59 was executed December 29, assuming the continuation of this much steeper downward trend than predicted by MG. However MAVEN ended up at much larger densities than expected, with many densities between 0.3 kg/km^3 and 0.4 kg/km^3. There was also an abnormally large periapsis density of 0.64 kg/km^3 two orbits after OTM-59 which caused the project concern. It was decided to not perform a special OTM right away but closely monitor the density, especially since the density might continue its recent decreasing trend. Special status meetings were held, but the project eventually waited till January 4th to decide on the next maneuver. It was decided to perform a 0.4 m/s (2.5 km) "up" OTM-60 on January 5th. That brought MAVEN down near the middle of the corridor.

B. Deep Dips

The deep dips were another challenging part of operations. MAVEN had only two days (three maneuvers) to safely get to densities which were over a magnitude larger than in the nominal orbit (2.0-3.5 kg/km^3 vs. 0.05-0.15 kg/km^3). A narrow density corridor was then to be maintained for five days, followed by two maneuvers over one day to get back to the nominal orbit. So the total duration of a "five day" science deep dip was eight days from an operations standpoint. Add to that a preceding day for planning the first deep dip walk-in maneuver, and a following day for a post deep dip accurate nominal science orbit prediction, and one gets a deep dip activity typically lasting for ten consecutive days.

Since the density behavior can change dramatically when such large changes in altitude occur, and may not be consistent with the MG model, MAVEN had to quickly but carefully walk in to the deep dip corridor. The walk-out was a little easier, since MAVEN already had a recent sampling of densities over the appropriate altitude range. The eight days of a deep dip have nine maneuvers. They are numbered as DDM-x1 through DDM-x9, where x is a letter in the range A-F (concurrent with the deep dip numbering).

There have been six deep dips to date. Figure 5 shows the geometry of each of the deep dips. The first four went smoothly, but there were difficulties getting into and staying in the corridor during the last two deep dips. The following are the UTC dates (and apoapsis orbit number ranges) of the six deep dips, as defined by the time of the first and last deep dip maneuver. (The deep dip maneuvers occur near 0 hours UTC.)

1. February 11-19, 2015 (A712–A754)
2. April 17-23, 2015 (A1058–A1091)
3. July 8-16, 2015 (A1500–A1544)
4. September 2-10, 2015 (A1801–A1843)
5. June 7-15, 2016 (A3284–A3327)
6. July 26 – August 3, 2016 (A3550–A3594)

Deep Dip 1 (DD1) occurred in February 2015 at Ls = 291 degrees, a little past the northern winter solstice. It investigated the dusk terminator. Since this was the first deep dip, the project was conservative in their maneuver decisions. Nevertheless only five maneuvers were executed: the three walk-in maneuvers (DDM A1-A3) and the two walk-out maneuvers (DDM A8-A9). No maneuvers were required for corridor control during the five days of science. With this first deep dip a conservative initial walk-in maneuver was performed of 3.3 m/s (20.8 km down in altitude). That was predicted to put MAVEN at an average density of just under 1.0 kg/km^3. The Navigation analyses after DDM-A1 showed that MAVEN actually got to a 1.2 kg/km^3 average density, only 20% off from the prediction. An 0.6 m/s (3.8 km down) DDM-A2 was chosen to get MAVEN near 2.0 kg/km^3. After DDM-A2 two low densities outside of the corridor were observed with an average of 1.6 kg/km^3. One additional density estimate became available while Navigation was working on its OTM recommendation, but it was much higher – 3.4 kg/km^3. The last density made the OTM decision more difficult. It was decided to perform a small 0.2 m/s (1.3 km down) DDM-A3. It turned out that this maneuver brought MAVEN into the middle of the science corridor. No further maneuvers were needed to maintain the density in the science corridor. Since only two maneuvers were available for getting back into the nominal science corridor, it was decided to perform a 3.9 m/s (24.2 km up) DDM-A8. It was predicted to move MAVEN down near a 0.21 kg/km^3 density, which was about where MAVEN ended up. A 1.2 m/s (7.5 km up) DDM-A9 was executed which got MAVEN into the middle of the nominal science corridor.

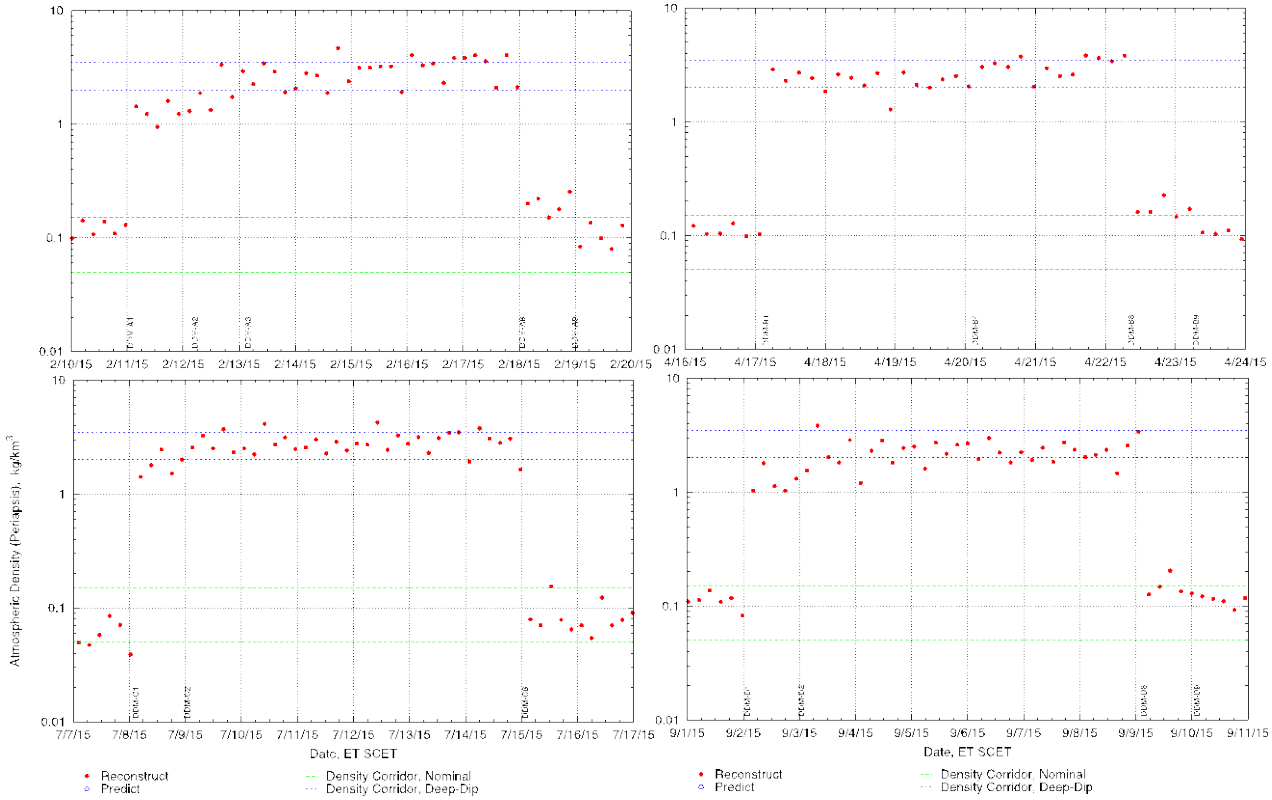

Figure 10. Atmospheric density during deep dips 1-4.

Deep Dip 2 (DD2) occurred in April 2015 at Ls = 329 degrees. Its purpose was to get information near the subsolar point. (MAVEN's periapsis was also at noon and 0 degrees latitude.) Only four maneuvers were required for this deep dip: one walk-in (DDM-B1), one corridor control (DDM-B4), and two walk-out maneuvers (DDM B8, B9). After the successful execution of deep dip 1, it was decided to be optimistic and pick a DDM-B1 maneuver of 5.7 m/s (36.0 km altitude decrease) to target MAVEN directly into the corridor at 2.8 kg/km^3. The achieved 2.5 kg/km^3 density was quite close to this prediction. The density drifted slightly lower with time, so a DDM-B4 corridor control maneuver of 0.4 m/s (2.5 km down) was executed. A 4.8 m/s (29.8 km up) DDM-F8 was executed to move MAVEN down to 0.19 kg/km3, leaving a little margin in case MAVEN overshot the predicted density. MAVEN got very close to the predict, around 0.17-0.18 kg/km^3. A 1.2 m/s (7.5 km up) DDM-B9 was executed to put MAVEN in the middle of the nominal science corridor.

Deep dips 3 and 4 also went nominally. Deep dip 3 (DD3) occurred on the night side of Mars, and was in the southern hemisphere at latitudes with strong crustal fields. It only required three maneuvers: two walk-in maneuvers (DDM-C1,C2) and one walk-out maneuver (DDM-C8). Deep dip 4 (DD4) investigated the southern terminator region. It only required four maneuvers: two walk-in maneuvers (DDM-D1,D2) and two walk-out maneuvers (DDM-D8,D9). MAVEN was at lower densities in the corridor after DDM-D2, but MG MY0 was predicting a slight increase in density. So no corridor control maneuvers were executed. However the increase in density never materialized, resulting in an average density of 2.3 kg/km^3. MAVEN was on the edge of the nominal corridor after the 3.3 m/s DDM-D8, so a 0.6 m/s (3.8 km up) DDM-D9 was executed to bring MAVEN near the middle of the corridor.

Deep Dip 5 (DD5) occurred in June 2016 at Ls = 167 degrees. It was designed to be at the dawn terminator, and occurred at northern mid latitudes, near equinox. Since the operations teams now had experience with four deep dips, and they had all been executed so well, one might have expected no problems with this deep dip. However DD5 turned out to be one of the more difficult deep dips. Although differences between the MG and actual density scale heights caused problems targeting to the corridors, the greatest problems were due to the large orbit to orbit density variability and the difficulty of getting a realistic average density from just a few points for use in making a maneuver decision. In fact, if one only looked at the density points in Figure 11, one would have difficulty correctly guessing where many of the maneuvers occurred. Six of the nine maneuvers were required. This included all three walk-in maneuvers (E1, E2, E3), one corridor control maneuver (E4) and two walk-out maneuvers (E7, E9). The

number of deep dip science days was decreased from five to four in order to add an extra day to the "walk-out" for a special NGIMS (Neutral Gas and Ion Mass Spectrometer) experiment.

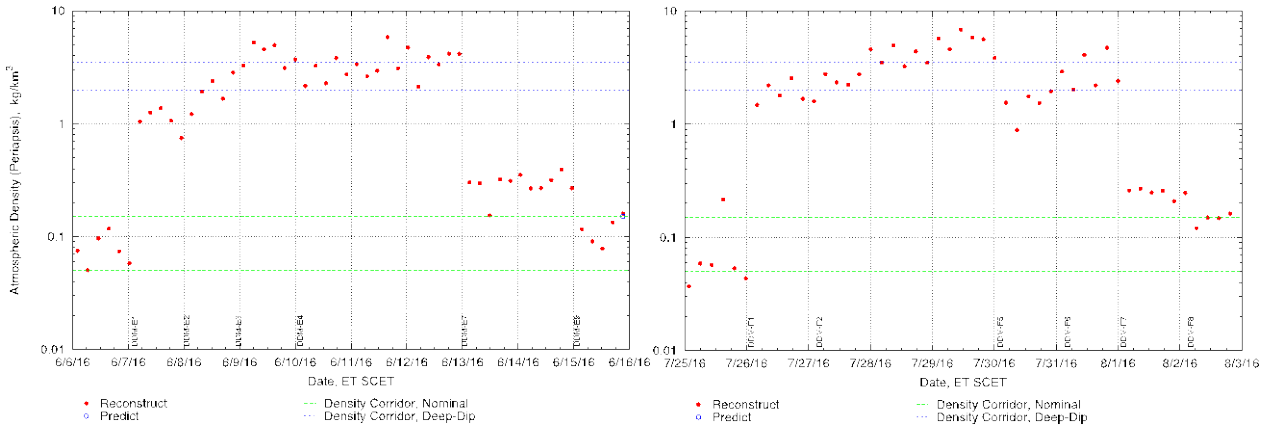

Figure 11. Atmospheric density during deep dips 5-6.

Three parameters can have a significant effect on deep dip decisions: the pre-DDM density, the effective density scale height over the DDM altitude change, and the post-DDM density. In the tight daily deep dip schedule, only three or four density points are available for determining an average pre-DDM and post-DDM density. If during the walk-in the assumed pre-DDM density is smaller than it should be, then a larger DDM will be chosen, which could result in the post-DDM densities being larger than desired. Also, the average density derived from the 3-4 reconstructed post-DDM densities (used for the next DDM decision) may not be accurate, thereby giving an inaccurate idea of where the DDM put MAVEN relative to the corridor, and implying an incorrect actual density scale height. As an example, the three density points after DDM-E2 implied that MAVEN was at an average density of 1.84 kg/km^3. This was much lower than the expected 2.7 kg/km^3 density. Thus it was decided to execute a 0.4 m/s (2.5 km down) DDM-E3. MG predicted that maneuver would get MAVEN up near 3.0 kg/km^3. The first density point after DDM-E3 was roughly where expected, at 3.3 kg/km^3. However the next three densities were dramatically higher at 5.2 kg/km^3, 4.6 kg/km^3, and 5.0 kg/km^3. Furthermore the peak instantaneous densities seen in the spacecraft accelerometer data were much higher than the Navigation values. This initially caused some project concern related to possible spacecraft and/or instrument "safing". Table 1 summarizes this information for all of the DD5 maneuvers. It gives the scaling factor Navigation applied to MG for the pre-DDM prediction, the pre-DDM density average (from only the points available for the DDM decision, and then for all available points after the fact), a description of the DDM decision (including the "targeted" post-DDM predicted density), and the post-DDM density (from only the points available for the next DDM decision, and then for all available points). Note that DDM-E3 targeted to approximately the same density as DDM-E2, but the actual densities after the maneuvers were very different.

Table 1. Deep Dip 5 maneuvers and density behavior.

Maneuver	*Nav MG Factor*	*Pre-DDM Density Average (kg/km^3)*		*Maneuver*			*Post-DDM Density Average (kg/km^3)*	
		DDM Ave	*Total Ave*	*ΔV (m/s)*	*ΔAlt (km)*	*Pred. ρ (kg/km^3)*	*DDM Ave*	*Total Ave*
DDM-E1	1.30	0.1	0.1	3.3	-20.6	1.2	1.23	1.10
DDM-E2	1.20	1.23	1.10	0.9	-5.6	2.9	1.84	2.01
DDM-E3	0.75	1.84	2.01	0.4	-2.5	3.0	4.51	4.14
DDM-E4	1.10	4.51	4.14	0.2	+1.2	3.7	2.57	2.85
DDM-E7	0.90	3.5	3.5	2.7	+16.6	0.33	0.25	0.29
DDM-E9	0.75	0.29	0.29	1.5	+9.3	0.10	0.095	0.11

Deep Dip 6 (DD6) occurred at the end of July 2016 at Ls = 195 degrees. Its focus was the antisolar region (midnight at the equator). There had been little if any observations in this region and near these altitudes by previous Mars orbiters. This was another difficult deep dip, primarily due to the low density scale heights observed. Six maneuvers were executed: two walk-in maneuvers (F1, F2), two corridor control maneuvers (F5, F6), and two walk-

out maneuvers (F7, F8). (As in DD5, the number of deep dip science days was decreased from five to four in order to add an extra day to the "walk-out" for a special NGIMS (Neutral Gas and Ion Mass Spectrometer) experiment.) The 3.6 m/s (22.4 km down) DDM-F1 targeted to a 1.1 kg/km^3 density. The first four post-DDM orbits showed that a 2.0 kg/km^3 density was actually achieved. A small 0.4 m/s (2.5 km down) DDM-F2 was executed to get MAVEN well into the corridor. On July 28 the densities seemed to jump by 100% to an average value of 4.3 kg/km^3, and with significantly more orbit variability. However the Atmosphere Advisory Group (AAG), composed of scientists examining the latest Mars Reconnaissance Orbiter (MRO) , Mars Odyssey (ODY), and MAVEN data, saw no indication of any significant changes in the atmosphere at the MAVEN altitude and latitude. However they did observe some quite small density scale heights from the MAVEN accelerometer data. That was consistent with the observed results of the DDM maneuvers. A DDM-F4 would have been executed to get MAVEN back into the corridor, but such a maneuver would have put MAVEN at risk of colliding with Phobos on July 30 (~19:55 UTC). So DDM-F4 was cancelled. The next day the densities were higher again, which caused some concern in the project. Also, the instantaneous density peaks seen in the accelerometer data were generally significantly higher than the Navigation densities. Fortunately these high densities resulted in there no longer being a concern of a Phobos collision with a maneuver. Due to this increasing density trend, it was decided to be safe and execute a 0.9 m/s (+5.5 km up) DDM-F5. MG predicted that DDM-F5 would put MAVEN at a 2.8 kg/km^3 density. However the MG effective scale height for DDM-F5 was 7.2 km, whereas it was thought that the actual scale height could be as low as 5 km which would put MAVEN down around 2 kg/km^3. The post DDM-F5 four orbit density was 1.438 kg/km3, so a small 0.4 m/s (2.5 km down) DDM-F6 was executed. DDM-F7 had similar results consistent with a much smaller scale height than MG. It dropped MAVEN down to a density of 0.25 kg/km^3 instead of the MG target of 0.5 kg/km^3. When the deep dip was reviewed, all of the discrepancies between MG predicted and actual post-DDM densities were consistent with the significantly smaller density scale heights which were observed. The AAG had seen many orbits with scale heights around 4 km – much smaller than the MG 7.2 km. These small scale heights were most common at the lowest altitudes around 120 km. The midnight location of this deep dip may have also been one of the reasons for such small scale heights. The large density variability in the middle of the deep dip further complicated corridor control.

VIII. Navigation Reconstruction Accuracies

Navigation has the requirement to reconstruct the spacecraft trajectory to within an accuracy of 3 km, excluding special situations. The pre-operations analyses[3,4] showed that, with nominal tracking scenarios of one DSN tracking pass per day, the reconstruction uncertainty would meet the 3 km requirement. This was true even for the worst case of a DSN passes scheduled at the beginning of one day and at the end of the following day (approximately a 36 hour data gap). Figure 12 shows a plot of the errors from these covariance analyses. This section will look at the actual reconstruction errors observed in operations to determine if Navigation actually met the 3 km accuracy requirement.

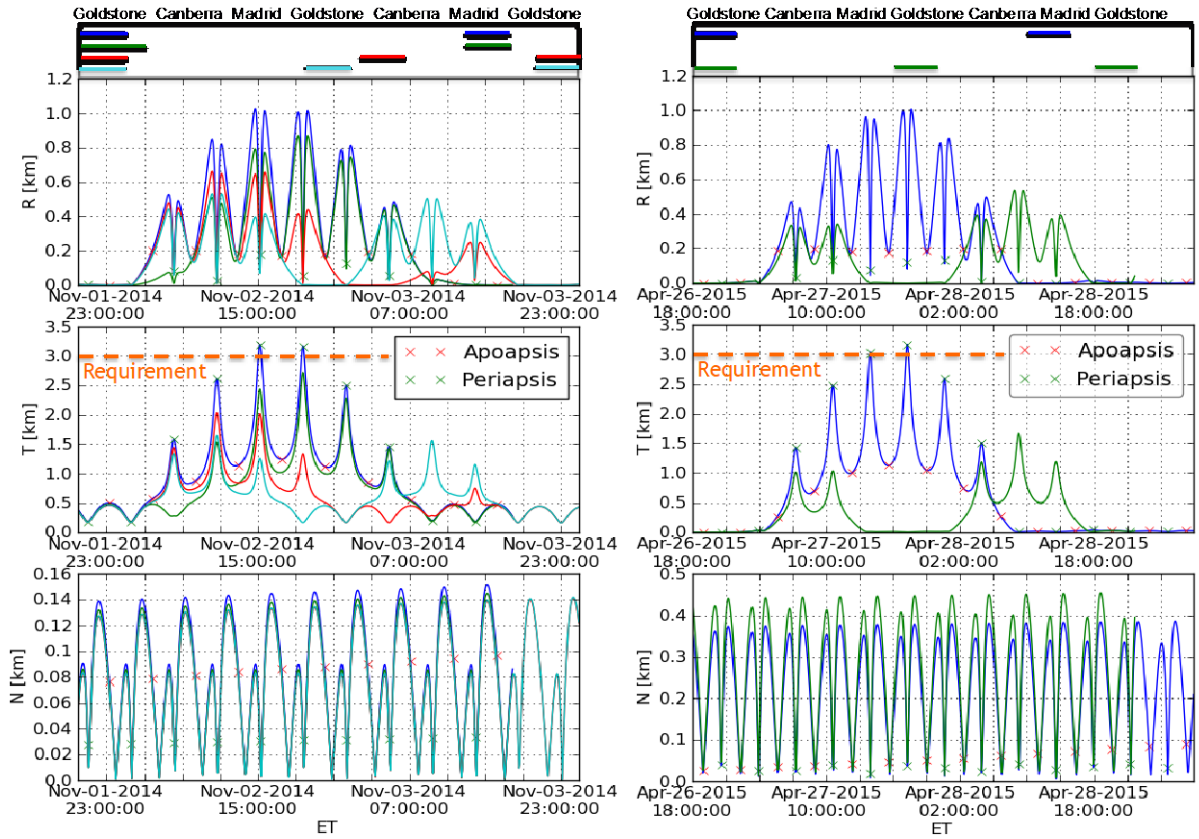

Figure 12. Orbit Reconstruction Capability with Regular and Maximally Spaced Tracking Passes.

Since Doppler data is an Earth-MAVEN line of sight measurement, the orientation of the MAVEN orbit relative to Earth can have a significant impact on the ability for Navigation to reconstruct certain components of the MAVEN position and velocity. Figure 13 shows these geometries via the inclination in the Plane-of-Sky coordinate frame (I_{pos}).* There are two singular cases. When I_{pos} = 90 degrees, the orbit is edge-on as seen from Earth. In other words, the orbit appears as a line from Earth's viewpoint. Thus the Doppler gives little information on the cross-track position of the spacecraft. However good information can be derived for the down-track and radial directions. When I_{pos} = 0 degrees, the orbit is face-on as seen from Earth. In this case the Doppler can give accurate cross-track information, but poor radial and down-track information. The left series of plots in Figure 12 are for a geometry which is the closest to face-on that MAVEN sees during its primary science mission. However the I_{pos} is still 20 degrees in this test case, so this ends up being representative of the nominal orbit geometry situation. The plots on the right side are for an I_{pos} of 90 degree geometry. As predicted, the normal component errors are much larger. Thus the edge-on orbits experience a noticeable degradation in the out-of-plane or normal reconstruction accuracy. However, since the normal errors are much smaller than the transverse errors, this is expected to have negligible impact on the ability to meet the reconstruction accuracy requirement.

* The I_{pos} is just what it says: the inclination of the MAVEN orbit to the plane of the sky as seen from Earth. The Z-axis is along the Earth-MAVEN. So an I_{pos} of 0 degrees means that the MAVEN orbit is "flat on" as seen from the Earth, or the orbit angular momentum vector is parallel to the Earth-MAVEN vector. An I_{pos} of 90 degrees means that an Earth observer only sees the MAVEN orbit as a line since the orbit is perpendicular to its view.

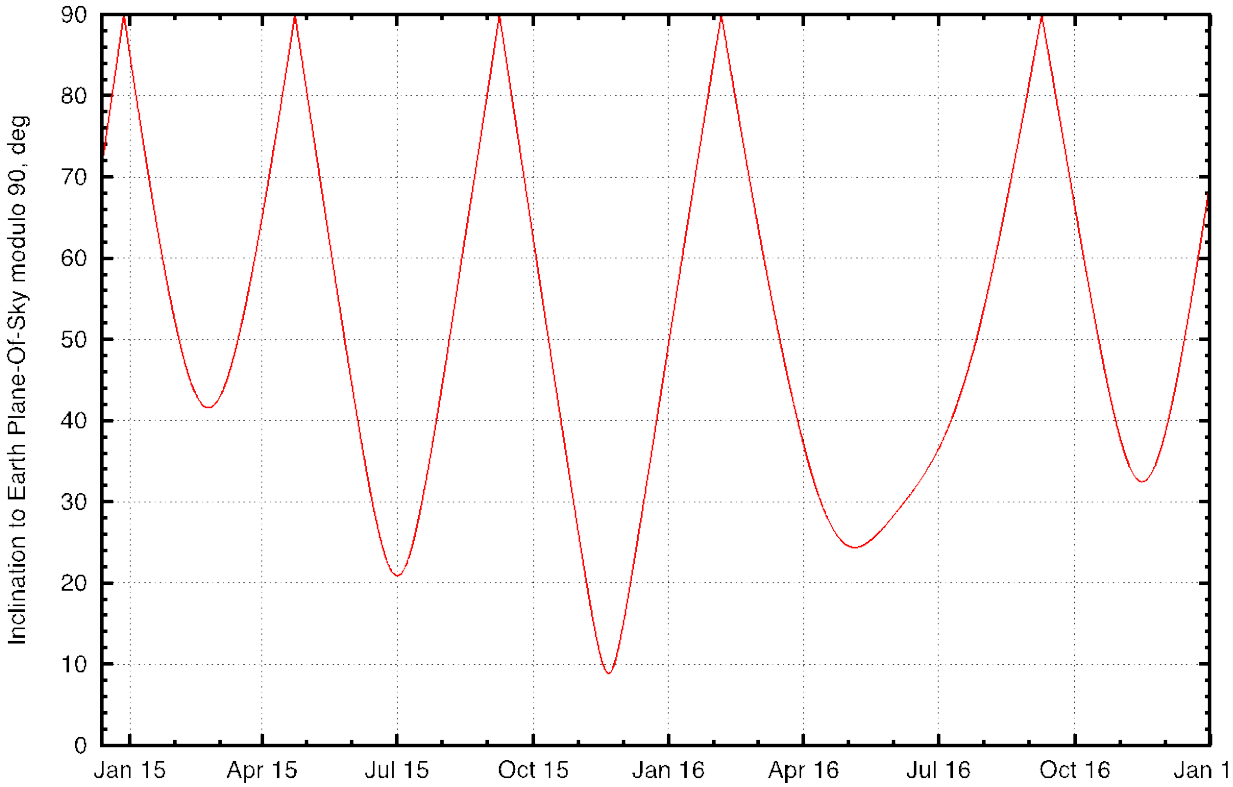

Figure 13. MAVEN orbit geometry as seen from Earth.

Although the amount of tracking data determines the size of the normal error, the shape of this error curve remains the same during and outside of the Doppler passes. On the other hand, the radial and transverse errors are tied down to small values during the Doppler pass, but degrade quickly in the gaps between Doppler. Thus any improvements in the radial and transverse errors in the 90 degree I_{pos} case are swamped out by the large error growth during the Doppler gaps. In operations, it has been extremely rare for MAVEN to have a tracking data schedule with the maximum gap shown in Figure 12 (blue curve).

Since the Navigation reconstructions are the only high quality trajectories, there is no obvious way to validate their accuracy. However Navigation can compare the overlaps between the different OD batches making up the reconstruction. A plot of those overlap differences in the position based RTN coordinate system* are shown in Figures 14-16. Each OD batch is anchored at the start and end with Doppler data, so these plots show the trajectory differences within a Doppler arc. Note that these overlap differences are generally much larger than implied by the plots in Figure 12. In those plots the position errors are tied down very accurately during Doppler data. The radial and transverse errors only grow large in the Doppler gaps. This discrepancy has also been noted on other orbiters, although it is much larger on MAVEN. It is thought to be primarily due to the known imperfections in Navigation's model of the actual atmosphere perturbations. This includes atmosphere volatility, the actual density profile around periapsis, winds, waves, etc.

This is why the effects of the orbit geometry (I_{pos}) are not obvious in Figures 14-16. One might be able to tie some spikes in the normal errors to dates of 90 degree I_{pos}. For previous Mars orbiters significant normal component accuracy degradation was noted within a couple of degrees of the edge-on geometry. One may also be able to see some geometry effects in late 2015 to early 2016. This is around Mars apehelion (Ls = 71 deg, 2015/11/21) when the atmosphere is relatively quiet. (It is also around Northern summer, and MAVEN is at low positive latitudes at that time. Northern Summer Solstice is at Ls=90, which occurs on 3 January 2016.) The position differences are relatively small for all components during this time. For the normal component, they are especially small during

* If **r** is the position vector from Mars to MAVEN, and **v** is the velocity vector of MAVEN relative to Mars, the RTN system is composed of the R (X) axis ("radial", defined by **r**), the N (Z) axis ("normal" or "cross-track", defined by **r**x**v**), and the T (Y) axis ("transverse", "down-track" or "along-track", defined by (**r**x**v**)x**r**).

November and December, near a face-on geometry. For the radial and transverse components, they tend to be smaller around the January-February time frame, closer to the edge-on geometry.

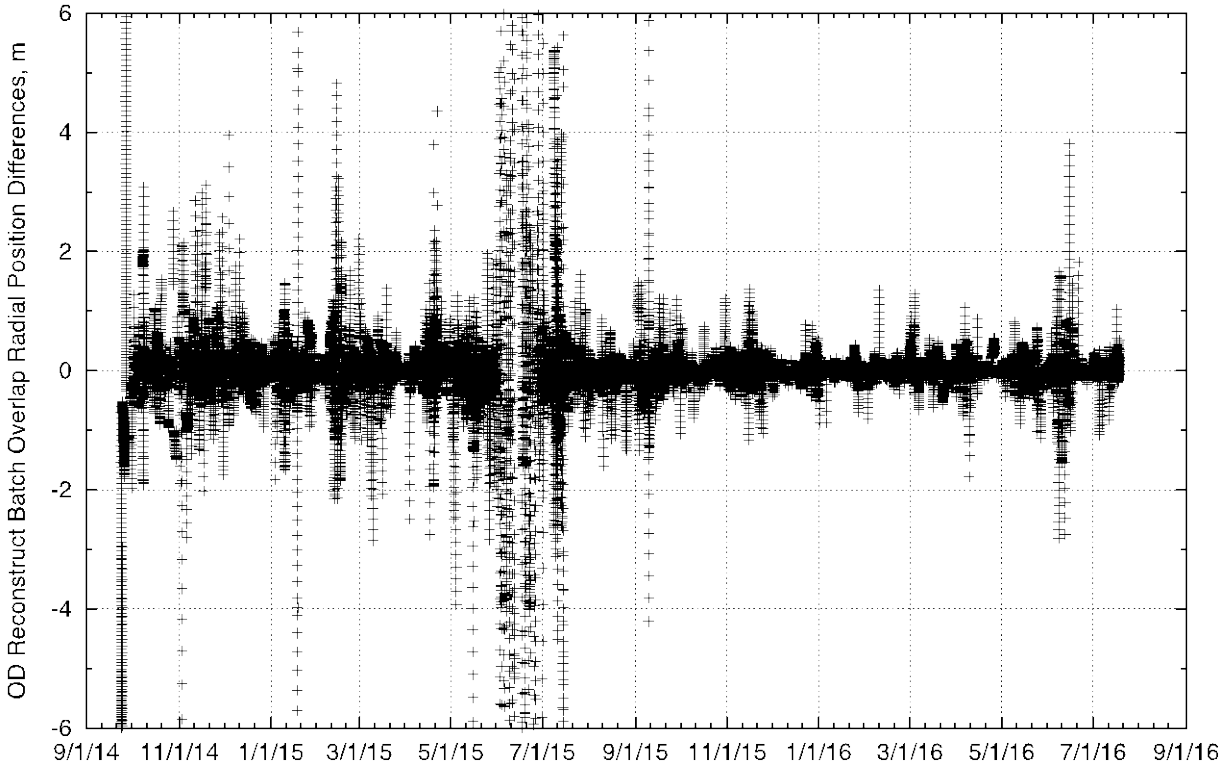

Figure 14. Radial difference between reconstructed OD batch overlaps

There are a few other obvious patterns which may be seen. The large errors in June 2015 are due to solar conjunction. The radial, transverse and normal errors got up to 40 m, 1900 m, 1000 m respectively. The differences are also significantly larger during the deep dips, although that is sometimes difficult to see from the resolution of these plots. There are a few cases with much larger errors. They are typically due to reconstructing a maneuver in that OD batch. Larger maneuvers especially cause problems, such as the deep dip walk-in, walk-out, and PCM's. There is rarely Doppler through a maneuver. Furthermore, a maneuver is often performed between station passes. In such a case it is difficult for the neighboring Doppler to reconstruct all parameters related to the maneuver and the drag passes within this data gap.

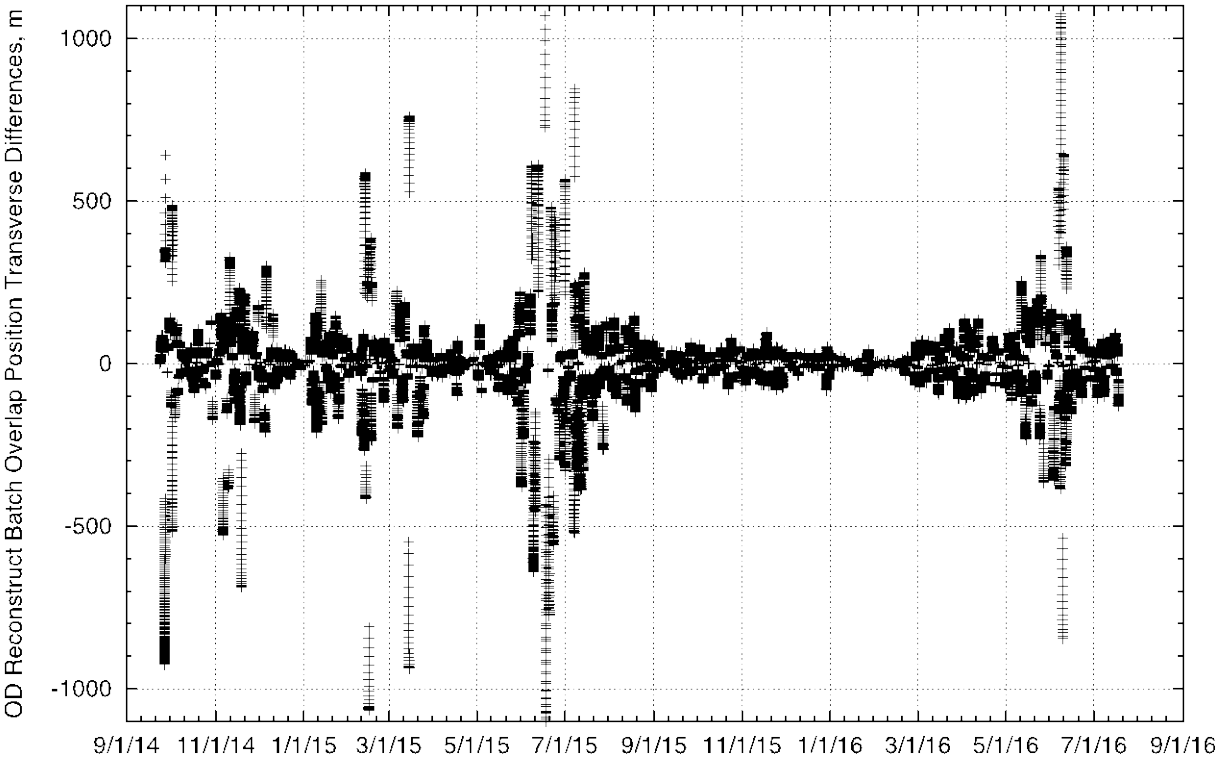

Figure 15. Transverse (Down-Track) differences between reconstructed OD batch overlaps

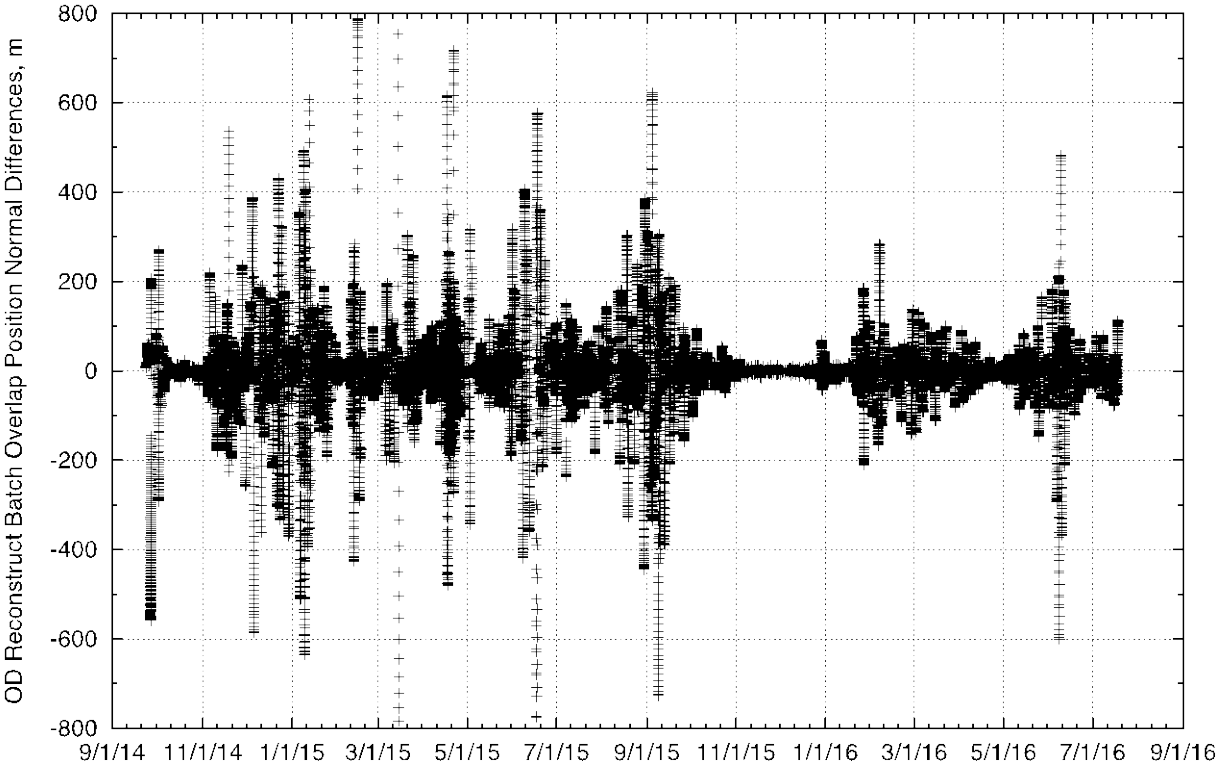

Figure 16. Normal (Cross-Track) differences between reconstructed OD batch overlaps

As previously mentioned, the overlap differences are generally much larger than implied by the Navigation Plan plots in Figure 12. There are several cases where the reconstructed OD batch overlap error gets up to 0.5-1.0 km (transverse and normal). Thus there could be concern that the transverse reconstructed error during the data gaps in these cases could be worse than the 3 km requirement. Fortunately the worst case DSN scheduling option shown in Figure 12 (blue) almost never occurs, so this is likely not a problem. Furthermore the reconstruct requirement is derived from a total NGIMS pointing requirement: the Navigation accuracy is only one of the many error sources contributing to this total NGIMS pointing accuracy, so there is expected to be some margin. So far Nav has heard of no problems that the project has had with its nominal orbit reconstructions. The reconstruction accuracy during the deep dip is not a problem due to the continuous Doppler tying down the reconstructed spacecraft state over the entire OD batch interval. In this case the above overlap difference plots can show the actual deep dip reconstruction accuracy.

IX. Navigation Prediction Accuracies

Estimating Navigation prediction accuracies are difficult. Atmospheric density is the major error source. The perturbation seen on the spacecraft from a periapsis pass (and thus the error) is a function of the atmospheric drag on the spacecraft, which is a function of both the density and the orientation of the spacecraft during a periapsis drag pass. The spacecraft can have four possible attitudes around periapsis, which complicates the Navigation analyses and predictions. The science teams meet weekly to decide which periapsis orientation(s) are preferred for science observations for the next week's sequence. Thus Navigation does not necessarily know the spacecraft periapsis orientation beyond the 3-15 days. This does not affect the important near term 20 second accuracy requirement, but could significantly affect predict accuracies beyond a week.

MAVEN is flying within a density corridor. Therefore based on the behavior of the atmosphere, MAVEN may need to perform OTM's to stay within the corridor. Navigation models OTM's in the predict at the weekly OTM slots in order to keep MAVEN in the corridor. However it is uncertain at that time what ΔV will be chosen, or if an OTM will even be executed. Some Monte Carlo studies have been performed which include a stochastic atmosphere model and attempt to model these OTM uncertainties in a reasonable manner.[11] Fortunately the only critical project predict requirement is the near term 20 second timing accuracy. Although there are no long term predict accuracy requirements, Navigation does need to supply expected long term prediction accuracies for COLA, lander relay support and future MAVEN science planning.

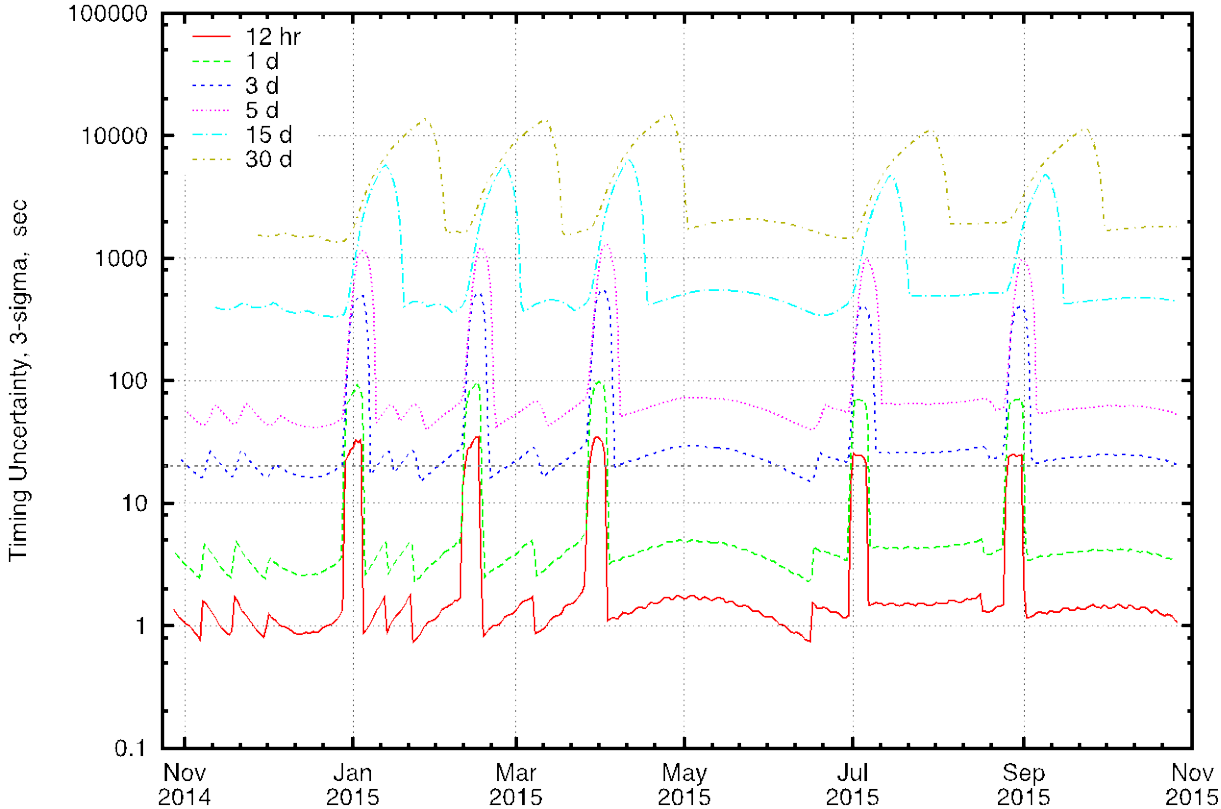

Figure 17. MAVEN science phase prediction uncertainty over primary mission.

A. Nominal Science Orbit Down-Track Timing Accuracy

Even though the 20 second down-track timing error is the only official project predict accuracy requirement on Navigation, there are several other time intervals over which estimation of the predict accuracy is important. The time intervals of most interest are:

- 0-2.5 days: 20 second prediction accuracy for spacecraft ephemeris and science instrument pointing.
- 2.5-14 days: Prediction accuracy needed to determine whether maneuvers are needed to avoid collisions with other bodies around Mars.
- 22-30 days: Prediction accuracy needed by Mars lander teams for scheduling relay passes.

Details on collision avoidance (COLA) and relay support will be discussed in later sections.

In modeling the prediction accuracies, OTMs are typically ignored. The pre-operations predict accuracy estimates for the primary phase are shown in Figure 17.[3,4] The spikes in the errors are due to the planned deep dips.[*] This plot shows that Navigation can consistently meet the 20 second timing requirement with a predict of just under 3 days. It is not known beforehand what orientation the spacecraft at periapsis will be. It is also not known where MAVEN will be in the density corridor. So this analysis assumed that the spacecraft was in the near maximum drag orientation ("drag pass" or "Fly-Z") and near the corridor upper density limit. Further analysis under these conditions refined the Navigation 20 second predict capability to predict to 60 hours or 2.5 days.

The actual orientation will significantly effect the predict quality. Whereas the Fly-Z orientation gives the maximum drag, the Fly-Y orientation gives near the minimum drag. The other two possible orientations (Sun-Velocity and Earth point) generally give drag effects between these two limiting cases, and vary with the relative positions of the sun, the Earth and Mars. Figure 18 shows estimated 3-sigma timing errors for these different periapsis orientations over the primary phase of the science mission.

[*] The first deep dip was cancelled in operations.

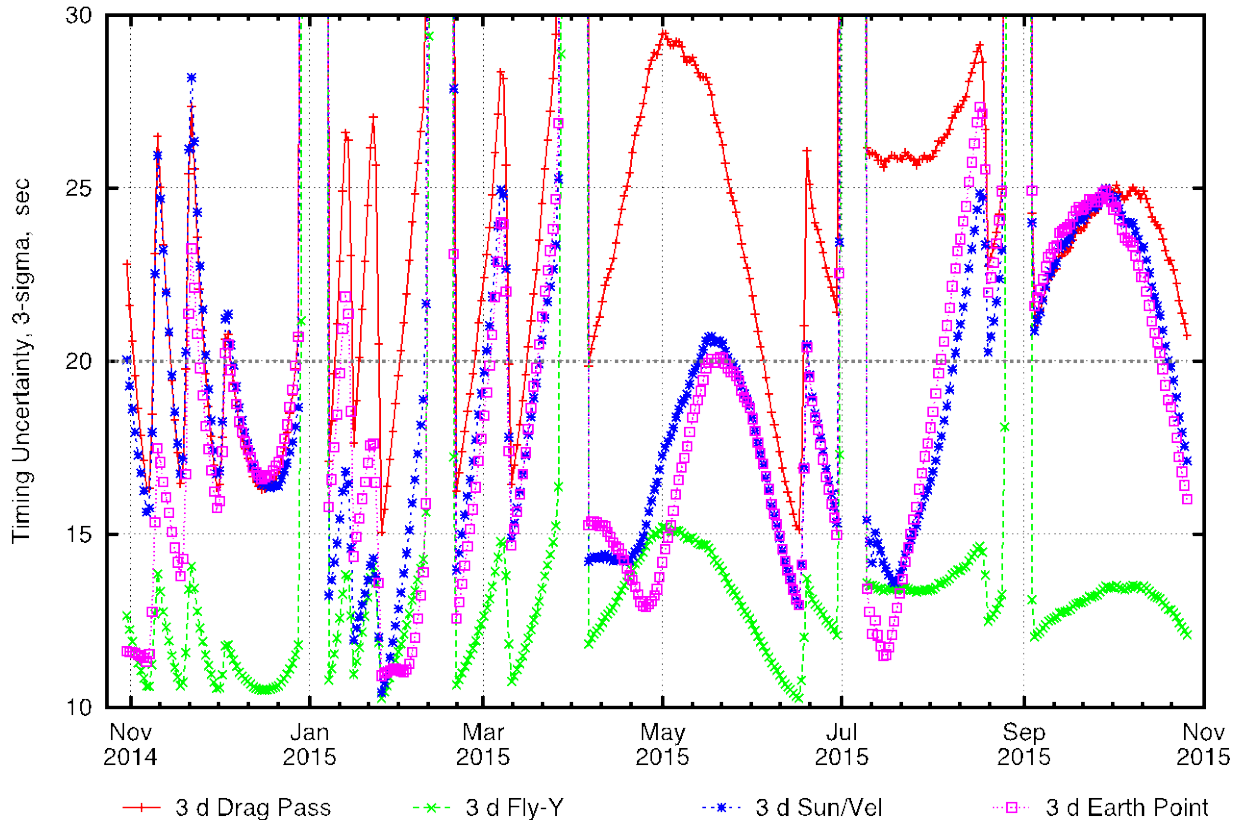

Figure 18. MAVEN science phase prediction uncertainties over primary mission: the effects of different spacecraft periapsis orientations.

It was originally expected that a large majority of the mission would be spent in a mode alternating between Fly-Y and Sun-Velocity. However MAVEN actually spent most of its time in the Fly-Y orientation. It turns out that the assumptions of a Fly-Z periapsis orientation, being near the upper density corridor limit, and 3-sigma density errors, results in the pre-operations estimated Navigation errors usually covering the actual operations prediction errors – despite the neglect of OTM effects. Also note that over long intervals (a month or more) OTM's tend to partially "correct" predict errors since they are putting MAVEN back into the density corridor.

Since the vast majority of the predicted timing error is due to the density (excluding OTMs), one can generate simple polynomial expressions to approximate the prediction errors. Such simple equations can be of use to people in order to have a rough understanding of the possible accuracy of any MAVEN nominal science orbit predict. In order to make them general, the equations make conservatism assumptions similar to those in the pre-operations error analysis. Two such equations are shown below, where Δt is the 3-sigma timing error assuming worst case spacecraft periapsis orientation (drag pass or Fly-Z) and ignoring OTMs.

$$\Delta t = 2.31 * t^2 \tag{1}$$

or

$$\Delta t = 0.1 + 3.9752 * t + 1.7560 * t^2 \tag{2}$$

These equations are quadratic in their behavior. This is because the error in the mean density accumulates in the same way on each orbit, leading to a linear increase in the period uncertainty, which accumulates into a quadratic timing uncertainty. Equation (1) gives a 20 second predict timing error after 2.94 days. Equation (2) gives 2.42 days till it gets to a 20 second predict timing error, consistent with the pre-operations analyses. For a 25 day prediction, Eq. (1) gives a 1444 second (24 minute) error whereas Eq. (2) gives a 1197 second (20 minute) error. Equation (1) is a nice very simple equation. It works well, but starts overestimating the error slightly as one gets close to a month prediction or longer. Equation (2) is not much more complicated, and gives errors similar to Eq. (1) over the first 10

days. After that its slower quadratic rate of growth results in slightly smaller error estimates. Since OTM's tend to partially correct the prediction errors, Eq. (2) could be considered slightly more reasonable if prediction accuracies on the order of a month are important. However, OTMs complicate matters. So the final equation preference may depend on the specific application and how conservative one wants the long term prediction errors to be.

When comparing these equations to the actual prediction accuracies in Figure 19, one notices:*

- All predictions are within these equations over the short span of nearly 7 days. (This span covers the predict time interval needed for a final decision to perform a collision avoidance OTM.)
- Over a 25 day interval, 84% of the predictions are always within Eq. (1), whereas 79% are always within Eq. (2).
- Many times the later OTMs partially correct the prediction, resulting in 89% of the predictions being within both Eqs. (1) & (2) at 25 days. (This is the prediction interval of interest for scheduling lander relay opportunities.)
- A significant portion of the "outlier" predicts occurred in 2014, at the beginning of the science phase and near Mars perihelion.

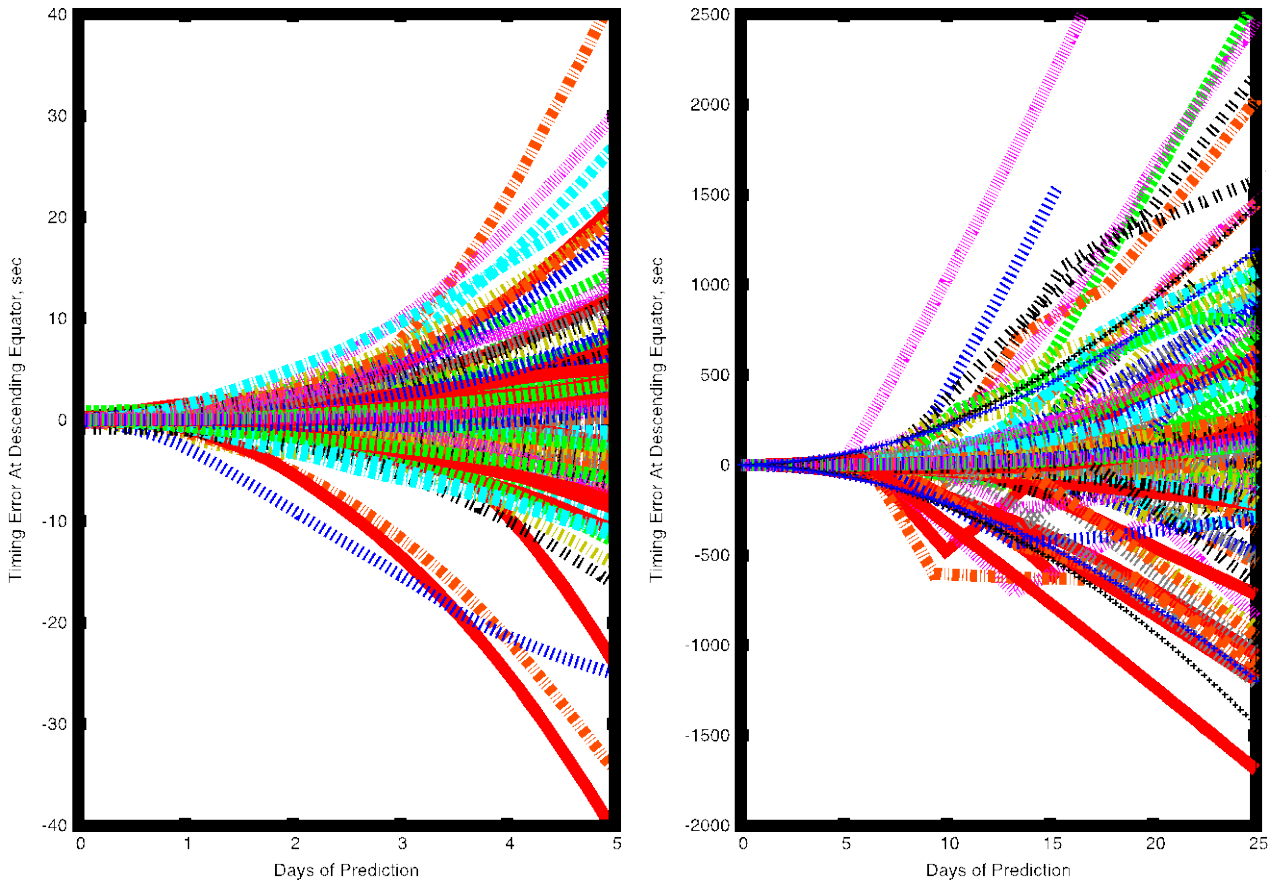

Figure 19. Actual Navigation prediction accuracies in science phase, through April 2016.

The accuracy of the atmosphere model prediction can have a large effect on the accuracy of the predictions. This effect is partly due to the accuracy in the predicted density profile (MG05 MY0, with a Navigation scale factor applied), and partly due to the resulting OTMs that are modeled in the prediction to stay within the density corridor.

Figure 20 shows the quality of the down-track predictions over two sample months. Most of the longer term (e.g. 25 day) "outlier" predicts occurred in 2014, as shown in the representative plot for December 2014. There were

* This calculation of accuracies only use data through December 2015 in order to not bias the results heavily towards the quiet density (accurate prediction) seasons.

several reasons for this: Navigation was refining models and processes; this was near Mars perihelion and the volatile atmosphere season (with MAVEN periapsis near the north pole); there were significant discrepancies between the predicted density behavior via MG and the actual density behavior; and the spacecraft periapsis orientations were giving near maximum drag perturbations. The November 2015 plot shows a more representative month, although slightly better than the average. February 2016 was an exceptional month, with all of the 25 day predicts having down-track timing errors less than 220 seconds. This was due to: relative stability of the atmosphere (i.e. "quiet" atmosphere, near Mars apehilion); density behaving similar to the Navigation model (MG MY0); a nearly zero trend in the density; and thus no OTMs being required during this time.

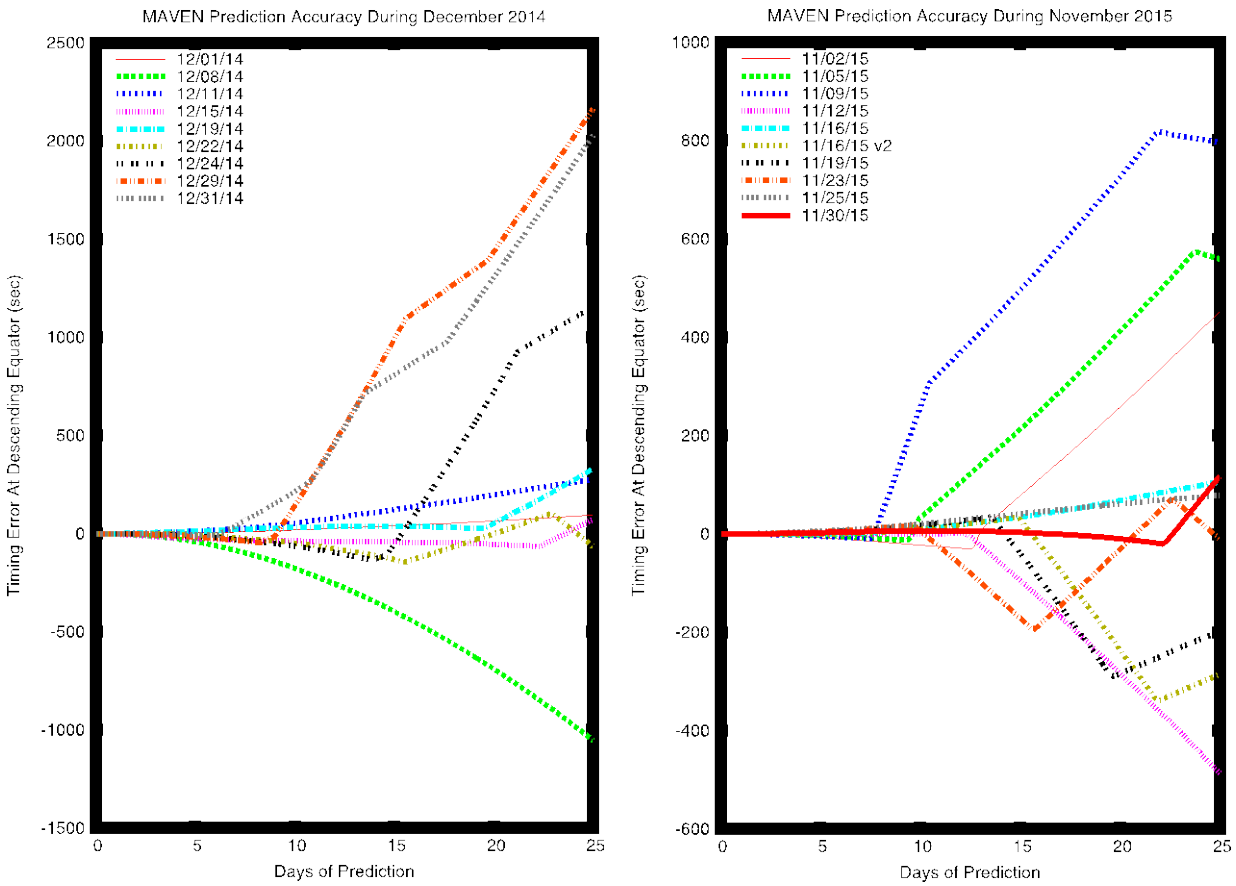

Figure 20. Examples of months of poor and good nominal orbit predictions.

However, even in such optimal situations, slight changes in the density trend and the uncertainty of whether an OTM is needed can have large effects on the prediction error. For example, all of the April predictions over 25 days were under 170 seconds – except for the first one on April 4th. That one had a 25 day timing error of 1700 seconds (28 minutes), an order of magnitude larger! Up to Monday April 4th it appeared that the densities were remaining nearly constant with only a very slight upward trend. This also agreed with the Mars-GRAM prediction, so no OTMs were included in the predicted trajectories. However, some large densities were observed immediately after this decision, and on Thursday April 7th a relatively sharp increase in the density trend was apparent, placing the periapsis density near the upper density limit of 0.15 kg/km^3. The Mars-GRAM Map Years 0, 1 and 2 also were starting to diverge in their predicted density behavior. So it was decided to perform OTM-74 that weekend to reduce the periapsis density, and it was included in that predict. This resulted in the April 4th prediction being quite inaccurate, and also affecting the preceding predicts but to a lesser degree. No further OTMs were executed till the deep dip 5 first walk-in maneuver DDM-E1 on June 7th. Plus MAVEN was in the Fly-Y minimal periapsis drag orientation, and the density behavior remained fairly consistent. Thus all of the remaining April predictions were very accurate. These effects may be observed in Figure 21, which shows the 25 day prediction timing errors as a

function of date. The date shown on the X-axis is the date at the end of the 25 days. The effects of OTM-74 can be seen on multiple predicts preceding this maneuver. The extremely accurate 25 day predictions after OTM-74 are also very obvious: they are less than 3 minutes.

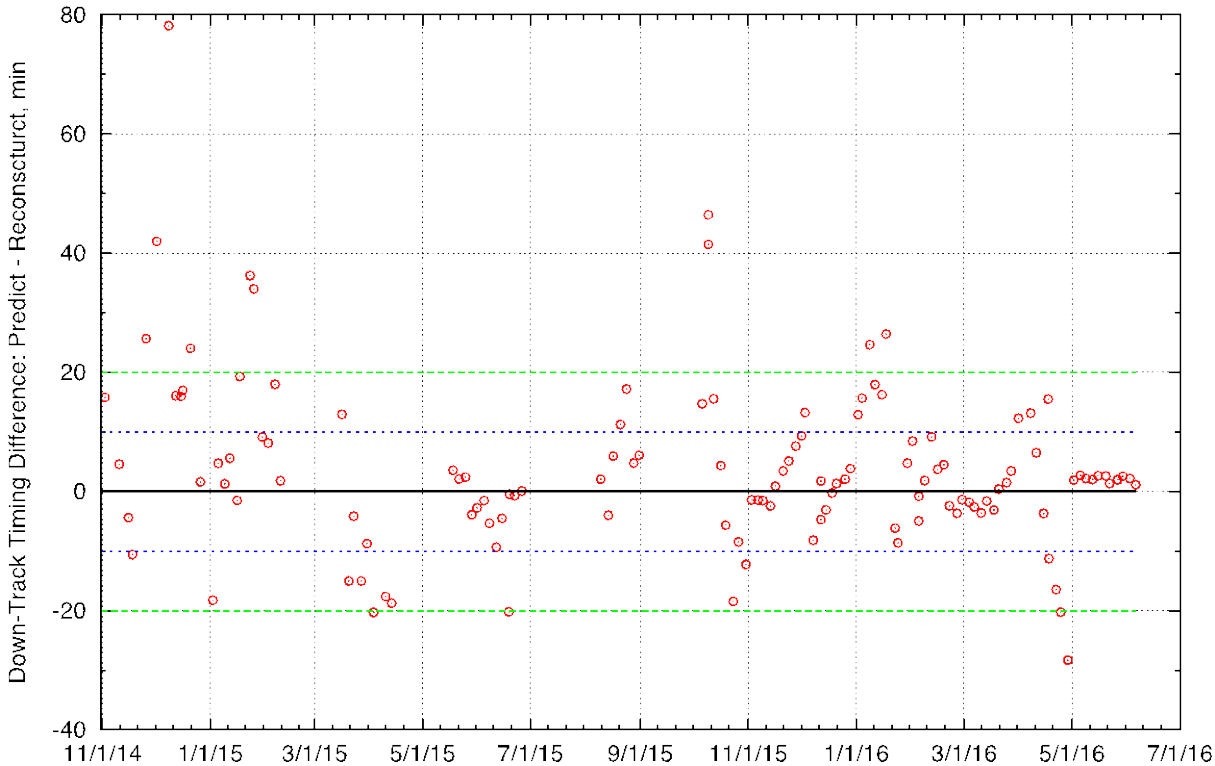

Figure 21. Progression in time of prediction errors over 25 days (134 orbits).

The only actual timing accuracy requirement is for Navigation to be able to provide a prediction accurate to within 20 seconds by the time of the next ephemeris upload onto the spacecraft. This time span is typically around 1-1.5 days, although contingency situations could stretch it out to over 2 days. As mentioned above, the Navigation Plan covariance analysis gave a 3-sigma limit of 2.5 days in order to stay within 20 seconds. So this allowed for the contingency cases, even with the conservatism of assuming a spacecraft periapsis orientation with the largest drag area. Figure 19 shows that the MAVEN prediction has always been within 20 seconds within 3.5 days. In fact, 5 day predictions have almost always been within 20 seconds. Due to the same reasons as described above, the 2014 predictions were less accurate. The predictions got a little better in the latter half of 2015 and early 2016 when the atmosphere quieted down as Mars approached apehelion. However, the improvement was not dramatic, and periodically one can have large errors. (For example, at the start of 2015 as described in the density section above.) The only period of consistently large improvement in the 5 day timing accuracies was after OTM-74, for similar reasons as given for the highly accurate 25 day predictions during that period.

B. Deep Dip Orbit Down-Track Timing Accuracy

For deep dips MAVEN reduces its periapsis altitude by 25-50 km to get to a Navigation density average between 2.0 kg/km^3 and 3.5 kg/km^3 – over an order of magnitude larger than in the nominal orbit. OTMs may be performed as frequently as once a day. Thus the predicted trajectory is much less accurate. On the other hand, the spacecraft is always in the "deep dip" periapsis orientation, eliminating the complication of the multiple possible periapsis orientations that occur in the nominal orbit. Pre-operations covariance analyses[3] showed that an updated ephemeris would need to be uploaded before the third predicted periapsis. In other words, Navigation could only meet the 20 second predict accuracy requirement over 2 orbits. Figure 22 shows that in actual operations the Navigation deep dip predictions were accurate over 3 orbits. (A 4.5 hour orbit is approximately 0.19 days.) Although there are no requirements for longer deep dip prediction accuracies, there has been some interest in such values. Figure 22 shows that the actual Nav deep dip predict error over 13 days can be as large as 40 minutes (2400 seconds), although it is

usually less than 25 minutes (1500 seconds). The predict error over 5 days was 10 minutes (although there was one outlier at 16 minutes). Over 2 days the maximum predict error was 5 minutes. Over only 1 day the predict accuracy was 44 seconds. There is only time for one possible maneuver in a 1 day prediction, and errors in its modeling do not have much time to propagate.

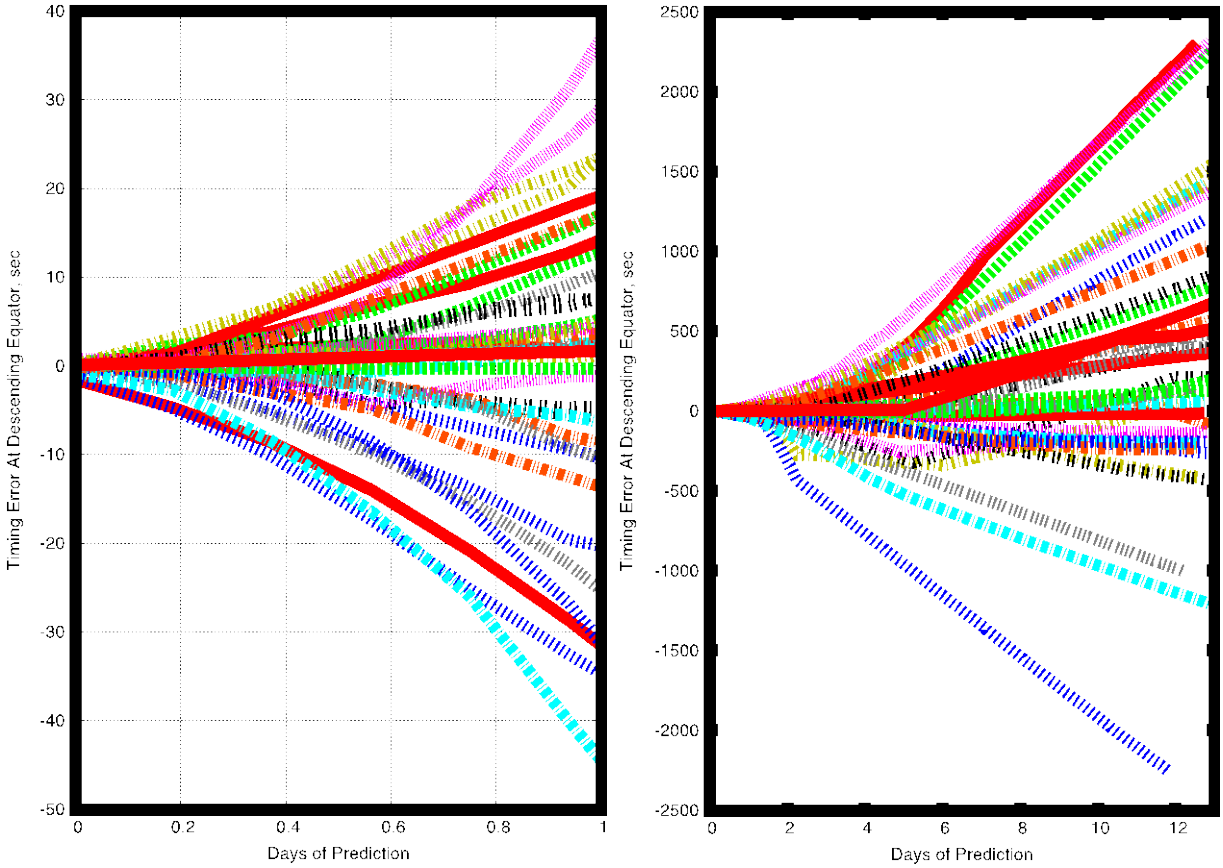

Figure 22. Actual prediction errors during the deep dips.

C. Predict Accuracies Of Other Five Orbital Elements

So far the predict accuracy discussion has concentrated on the down-track position or timing error. However the state of a spacecraft is specified by 6 parameters. Thinking in terms of orbital elements, the timing error is equivalent to the true anomaly error. The shape of the MAVEN orbit (semi-major axis, eccentricity) is well known compared to the true anomaly error. Similarly the orientation of the orbit in space (inclination, longitude of ascending node, argument of periapis) is also well known. The MAVEN Navigation accuracy capability for these other five parameters is much worse during deep dips than in the nominal science orbit, but still satisfies the needed NGIMS pointing accuracy. Thus the less accurate deep dip capabilities were set as the requirements on these five parameters for both the deep dip and the nominal science orbit. Figure 23 shows the predicted apoapsis orbit element errors for a representative nominal science prediction from December 7th, propagated out to December 26th, 2015. Each plot contains three curves. The predicted value of the parameter, the actual (reconstructed) value, and the difference between the predicted and reconstructed value (via the right-hand Y-axis). The 1.2 m/s down OTM-56 at A2317 (December 8th) and the 1.8 m/s down OTM-58 at A2391 (December 22nd) are obvious in the plots of the semi-major axis, eccentricity, and periapsis altitude, although only the latter OTM is obvious in the plot of the error. The first OTM is executed only a little over a day of prediction, so the prediction has not had enough time to drift off enough for OTM effects to be seen in the error. The second OTM is after 15 days of prediction, and has a different ΔV than modeled in the predicted trajectory. The OTMs are very difficult to detect in the plots of the angles defining the orbit orientation (inclination, longitude of ascending node, argument of periapis). In fact, the OTM effects are on the order of the variation in the angles between the one day reconstruction analyses. It is not till

the last OTM that a small but appreciable effect can be seen in the longitude of ascending node and argument of periapsis. (The very stable inclination does not even show a significant effect for this last OTM.) This is as one would hope, since the OTM ΔV should be entirely within the orbit plane. Therefore the actual orbital element errors are very small, with the only significant changes occurring from OTMs in the orbit shape parameters – and these are typically due to the OTM modeled in the prediction having a different ΔV than what was actually executed. Even with these mismodeled OTM effects, the orbital element prediction errors are far below the requirements.

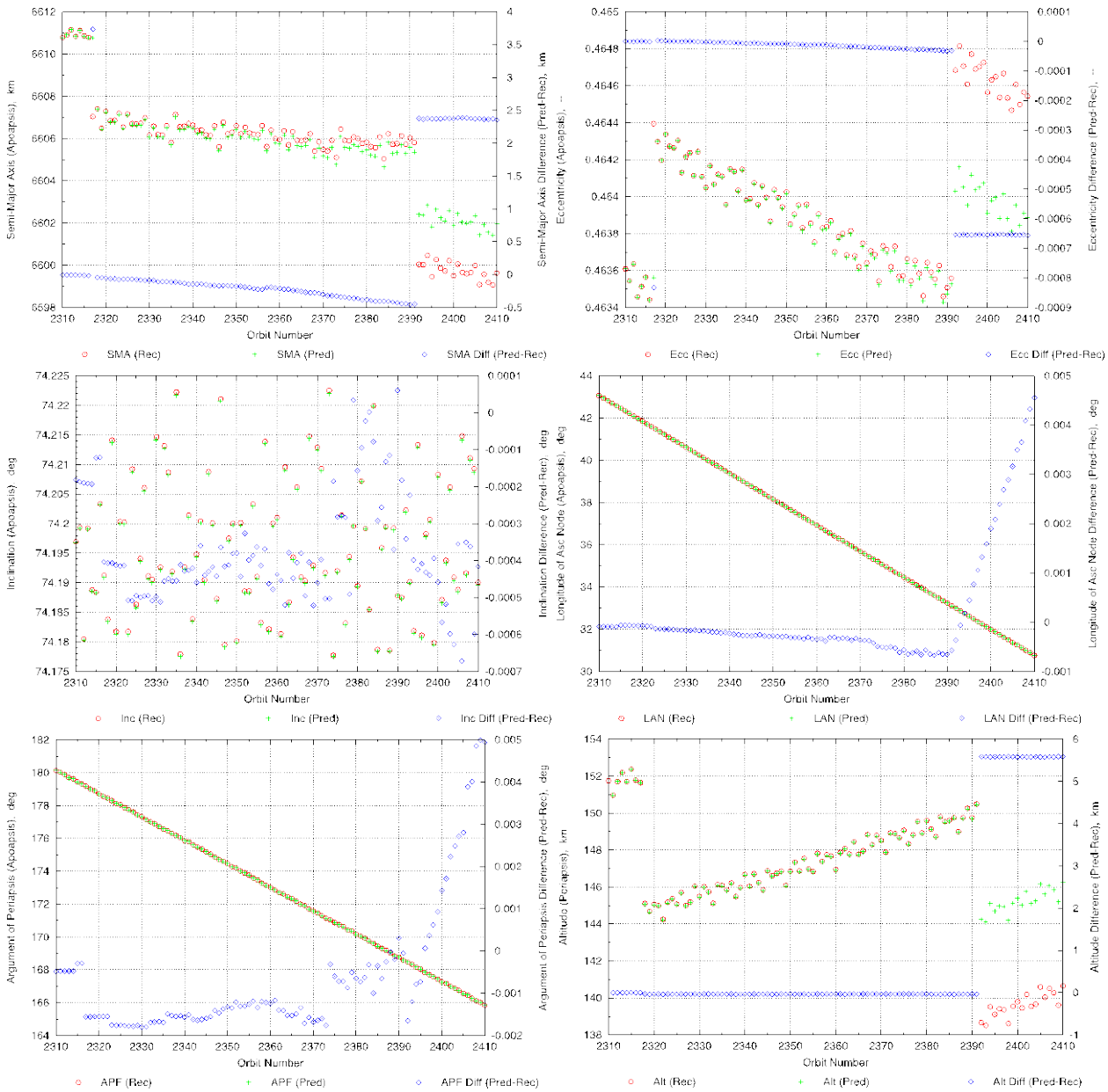

Figure 23. Orbital element prediction accuracy example for the nominal science orbit (Dec 7, 2015).

Figure 24 shows the predicted apoapsis orbit element errors for a deep dip science prediction from June 9-26, 2016. It is for one of the worse deep dip predicts in terms of orbital element accuracies. The deep dip ends with DDM-E9 at A3327 (June 15, 2016). The maneuvers that were executed were DDM-E4 at A3300, DDM-E7 at A3316, DDM-E9 at A3327, and OTM-85 at A3382. (DDM-E8 was modeled in the predict, though it was not executed.) Again, the OTM mismodeling is evident in the orbit shape parameters (semi-major axis, eccentricity, altitude), but on the order of the differences between the 2-4 orbit reconstruct analysis batches in the orbit

orientation parameters (inclination, longitude of ascending node, argument of periapis). Even in this case the orbital element accuracies are significantly better than the requirements.

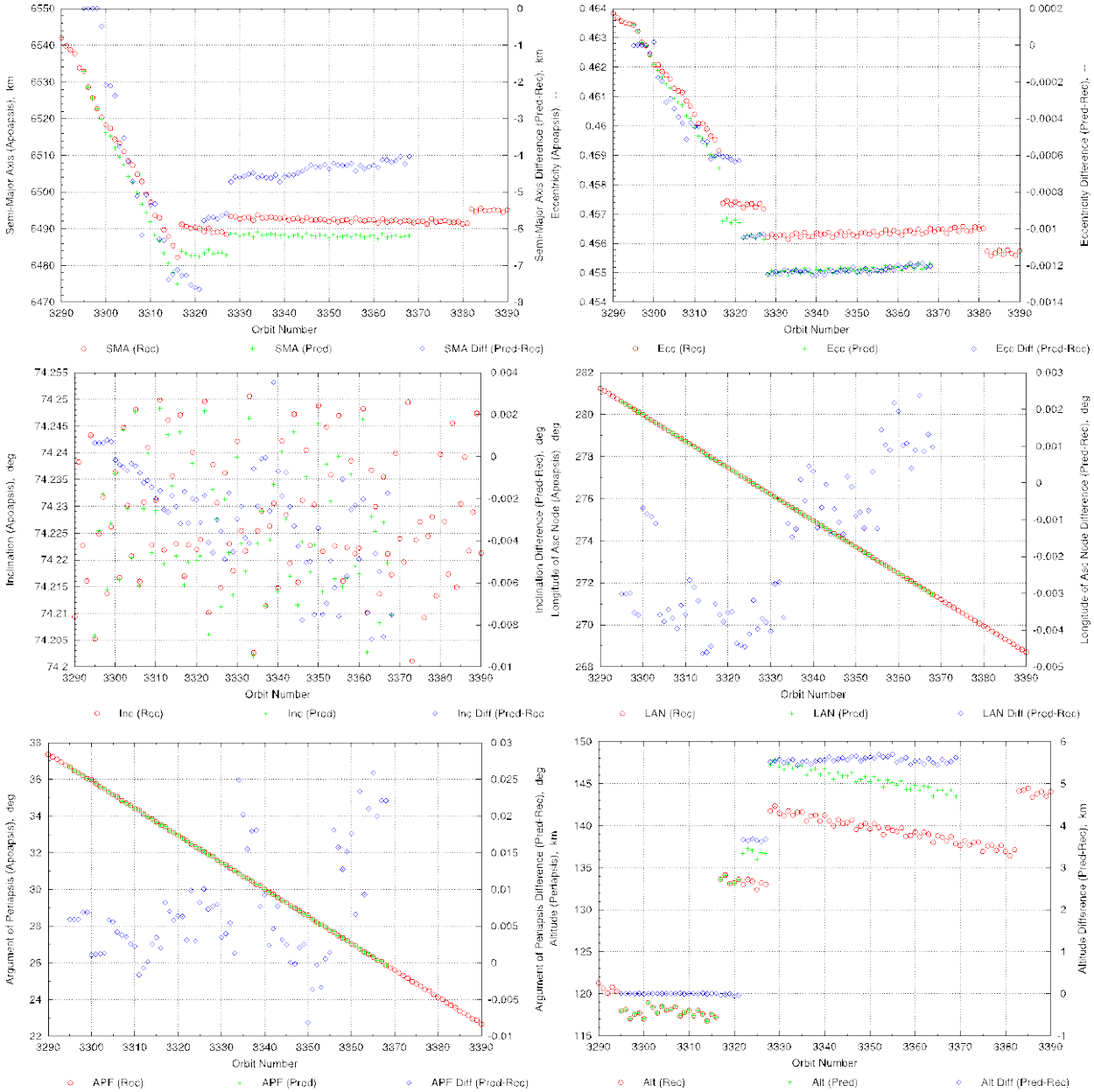

Figure 24. Orbital element prediction accuracy example for the deep dip (June 9, 2016).

X. Collision Avoidance

The space around Mars is becoming increasingly crowded. Besides MAVEN, the NASA spacecraft Mars 2001 Odyssey (ODY) and Mars Reconnaissance Orbiter (MRO), as well as European Space Agency's Mars Express (MEX) and the the Indian Space Research Organization's Mars Orbiter Mission (MOM) are all currently operating in orbit, in addition to the natural satellites Phobos and Deimos. Though an impact is extremely unlikely, particularly between two spacecraft, the consequences would be catastrophic, so efforts must be taken to ensure that any risks of collisions are avoided. MAVEN generally has the lowest periapsis altitude, and thus the most significant drag perturbations. As a result the MAVEN trajectory predictions are the least accurately known, and MAVEN has a streamlined maneuver process and frequent maneuver capability to help it maintain its desired orbit. Therefore the

MAVEN trajectory prediction and accuracy drives any collision avoidance (COLA) decisions, and MAVEN has the most convenient maneuver strategy for dealing with COLA issues. So MAVEN has taken on the prime responsibility for collision avoidance (COLA) with other spacecraft while in its science orbit. It must also avoid Phobos, whose orbit it periodically crosses.

To keep the problem focused and tractable, MAVEN uses a nodal analysis strategy, similar to what MRO initiated nearly a decade ago.[8] The shape of a Mars spacecraft orbit is fairly stable. It is the timing of the spacecraft within that orbit which is relatively poorly known. Thus MAVEN looks at when its orbit plane crosses the orbit planes of other objects around Mars. It then determines when the orbits between MAVEN and another body nearly cross in this intersection of planes. This gives COLA "seasons" where possible collisions could occur and thus careful attention must be paid to the spacecrafts. Since the orbits are relatively stable, these COLA seasons can be determined well in advance. MAVEN often calculates COLA seasons a year or more in advance. As COLA seasons get closer, updated analyses typically shift a COLA season very little if at all. Finally, if both spacecraft are at an orbit crossing at nearly the same time, a possible collision may occur. Since the uncertainty in the spacecraft position or timing within its orbit is relatively large, this can only be realistically examined as one gets close to a COLA season.

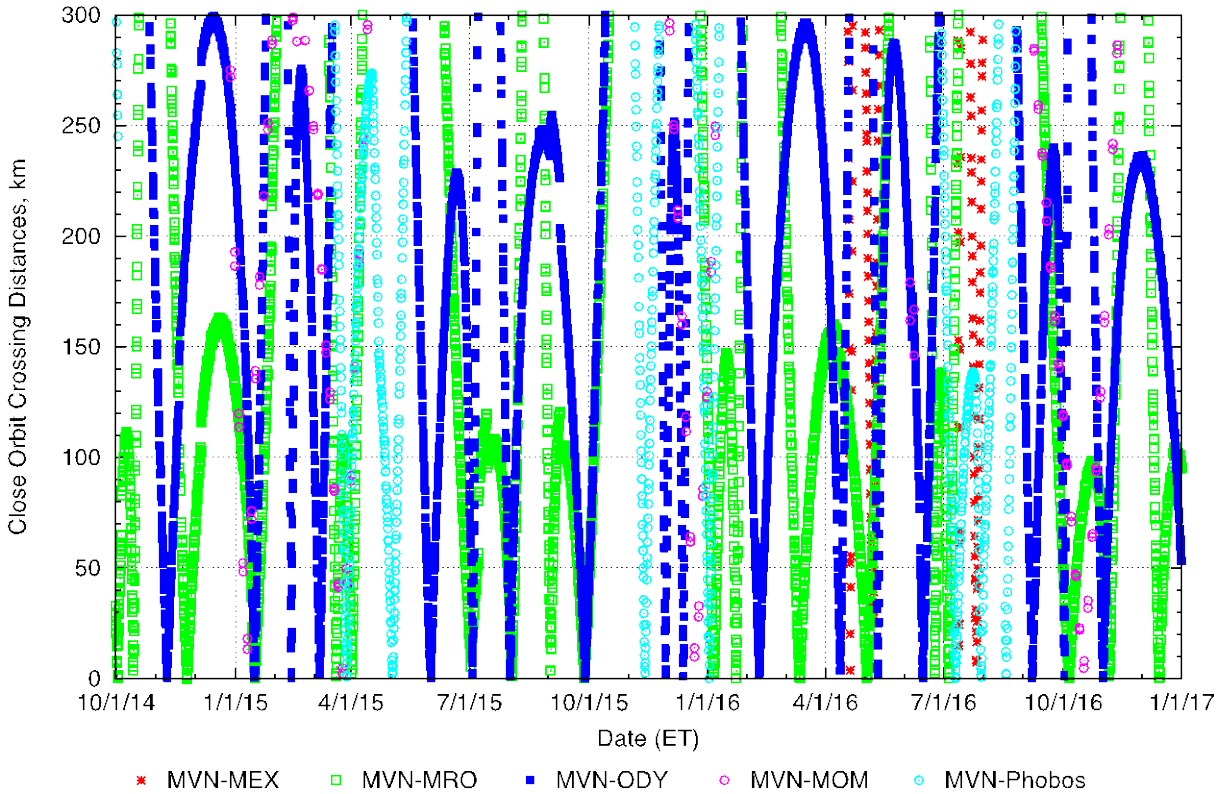

Figure 25. MAVEN COLA seasons with bodies orbiting Mars.

Figure 25 shows the distances between the orbits of MAVEN and other objects at the place where their orbits cross. One can see that MAVEN has collision opportunities with all of the other spacecraft and Phobos. MAVEN has weekly OTM slots for corridor control. They typically occur on the weekend, with an OTM decision on the preceding Thursday. They can also be used for COLA, if necessary. In this weekly scenario, an OTM would control a COLA possibility predicted 3-10 days in the future. However, due to MAVEN's low altitude and relatively high periapsis densities, the MAVEN prediction uncertainty grows rapidly in time. So planning a COLA related OTM for an event 10 days in the future would require a relatively large maneuver to get MAVEN outside of the uncertainty envelope. However MAVEN does have two communication passes per week, on Tuesday and Friday. As a result, a special COLA OTM decision can be made on Monday for a Wednesday (or late Tuesday) maneuver. This schedule decreases the maximum prediction till a possible COLA event to 6 days, thus dramatically reducing the maximum prediction error relevant for COLA – and thus the likelihood of needing to perform a COLA maneuver. Therefore MAVEN assumes that it has two OTM possibilities per week for collision avoidance, if necessary. Details of the

Navigation prediction capabilities over this length of time are given in the preceding secion IX (Navigation Prediction Accuracies).

Because of MAVEN's large prediction errors, one cannot avoid COLA situations with earlier maneuvers. However, one can reduce the likelihood of a COLA event. Also, the accuracy of the predict is dependent on the spacecraft periapsis orientations during that time, as described in the preceding predict accuracy section. So as one starts nearing a COLA event, one can often tweak the corridor control OTM decisions to still be reasonable for corridor control yet also reduce the likelihood of a future COLA problem. This decision making has often been used on MAVEN, and has so far allowed MAVEN to avoid a COLA specific maneuver. Figure 26 shows the actual closest approaches MAVEN has had with other objects around Mars during its science phase. Note that this plot does not show the position components of the close approach distances (e.g. radial, down-track/timing, cross-track distances; range between the nodes of the orbits). So, for example, some of the closest ones may have been out of the MAVEN orbit plane and thus had much less probability of collision than larger close approach distances. The closest encounter was 28.5 km to MRO. Almost all of the close encounters were with MRO and ODY, with most of the closest ones (below 100 km) being with MRO. MAVEN did get within 100 km of MEX in October 2015, at which time there was some additional interaction between Navigation and ESA to ensure that MAVEN correctly interpreted the collision probabilities. MAVEN performed some special science observations near Phobos close encounters in the middle of 2015. The last Phobos close approach on the plot was 253 km on July 29. This was a more challenging situation since MAVEN was in deep dip 6 at that time, and the OTM that would bring MAVEN back into the density corridor would greatly increase the likelihood of a collision.

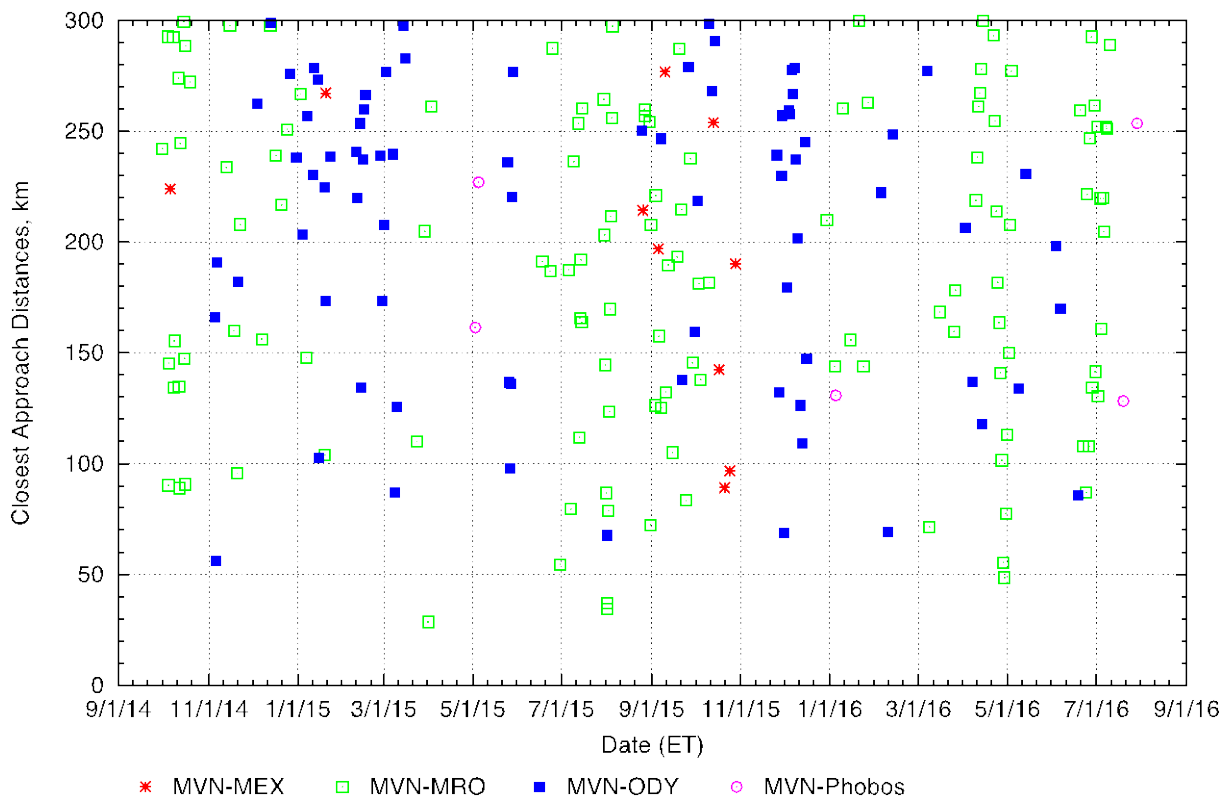

Figure 26. Actual MAVEN closest approaches to bodies orbiting Mars.

The spacecraft are essentially point masses compared to MAVEN's predict errors. However the dimensions of Phobos must be taken into account in these COLA analyses. Phobos is not circular, and its larger diameter is 13.4 km. Also, its larger down-track position accuracy is 15 km for the satellite ephemeris MAVEN is using (16.5 km propagated to 2016). Thus a radial "threshold" limit for the closest approach to Phobos is taken as 30 km. MAVEN's speed relative to Phobos at the crossing of the two orbits is ~2.2 km/s. So an orbit crossing timing

threshold of 15 seconds is assumed.* MAVEN Navigation prediction errors must then be added to these threshold values to determine the possibility of a collision. Although there is a some conservatism here due to this simplified Phobos model, it seemed reasonable for the time sensitive operations environment and the uncertainties of COLA analyses.

The Jet Propulsion Laboratory (JPL) Mission Design and Navigation (MDNav) section has an automated COLA process called MADCAP[12] running daily which gives COLA information on all of the operational orbiters and moons around Mars. If, within 14 days, a close approach is within a certain limit, the MADCAP process will mark it as a "red" event. This daily COLA information is sent out to a small group of people related to the Mars orbiter projects, the Mars Program Office and the MDNav section. Due to MAVEN's large prediction errors and frequent OTM capability, MAVEN does not actively pursue any COLA mitigations for a 14 day red event. Rather, MAVEN waits until it gets close to the appropriate OTM that COLA mitigation, typically within 3-10 days of the COLA event. Usually by that time this red event disappears due to smaller predict errors over the shorter predict interval. MADCAP uses polynomials as a function of time for calculating the "red limits" for the orbit crossing distance and orbit crossing timing, and/or uses constant close approach limits. However the appropriate polynomials for MAVEN depend on the spacecraft periapsis orientations and the position in the density corridor – neither of which may be known that accurately except over the next few days. Therefore, the MAVEN polynomials assume a conservative periapsis attitude and density. This strategy works well for the general MADCAP daily automated e-mails, giving timely status information. MAVEN Navigation performs higher fidelity COLA analyses internally at each predict delivery with the latest model information available to them, as an OTM decision is part of the predict delivery. This allows the highest fidelity COLA analysis with the latest MAVEN predicted information to be used.

XI. Mars Landers Relay Support

One of the expectations was that MAVEN would support Mars landers as a relay asset after its primary mission. The vast majority of received lander data is first relayed to an orbiter around Mars, which then relays it back to Earth. To support a relay "pass", MAVEN must rotate the entire spacecraft to point its Electra antenna to the lander, then rotate the entire spacecraft to point the high gain antenna towards Earth, taking time away from science observations. Thus MAVEN's relay support responsibilities were limited to emergency support during the one Earth year primary mission. Similarly, the required MAVEN relay support during its first extended mission (second half of its first Mars year) was planned to be very limited. The one exception was a series of test campaign relay passes with the landers Opportunity (MERB) and Mars Science Laboratory (MSL). This test was to prepare for operational support of the InSight lander and ExoMars 2016 Entry Descent Lander (EDL) Demonstrator Module (EDM) in the latter half of 2018. The MAVEN relay communications with MERB would be similar to those with InSight, whereas the MAVEN relay communictations with MSL would be similar to those with EDM. With the postponement of the InSight launch by two years, the number of relay pass tests with MERB were reduced. MAVEN has so far supported several successful relay pass tests with both MSL and MERB.

Due to the time it takes to plan and schedule MAVEN science and sequences, along with time needed by the landers, a requirement was levied that a lander request for a relay pass must be made a minimum of 22 days before that event. For MRO and ODY that lead time does not cause a significant problem. However for MAVEN this lead time means that the predicted MAVEN position they are using to determine a relay request is poorly known. The actual geometry of MAVEN with respect to the lander may not change that much, but when MAVEN is at that geometry is quite uncertain (i.e. large timing or true anomaly error). Figures 19-21 show that the MAVEN down-track timing error could be half an hour after 25 days, although the vast majority of cases are significantly smaller. The preceding section IX (Navigation Prediction Accuracies) discusses such prediction accuracies in detail. If one uses the COLA predict timing error polynomial, the 25 day error is 20 minutes. If one uses the simple quadratic term equation, the error is 24 minutes. Such large possible predict errors make relay planning a challenge. Examining Navigation trajectory predictions through December 2015, 89% of them were within 20 minutes after a 25 day prediction. The relay teams often plan their relay sequences so they can be shifted 10 minutes earlier or later. Only 58% or the predictions were within 10 minutes. (See Figure 21.) The recent MAVEN relay tests have been a success, but they have occurred during the recent quiet period of the atmosphere. During this optimal time (March-May 2016) 83% of the Navigation predictions were accurate to within 10 minutes after 25 days. MAVEN will support the ExoMars 2016 EDM lander relay operations (a 14 day period following EDM landing on October 19th, 2016). However this will be occurring around Mars perihelion, during a more volatile atmosphere time when MAVEN predictions are expected to be relatively poor.

* (30 km) / (2.2 km/s) = 13.6 km, rounded up to 15 seconds.

XII. Future Plans

MAVEN's Extended Mission #1 (EM-1) ends on September 30th, 2016. At that time MAVEN will have been in its science phase for almost two Earth years, or one Mars year. MAVEN has been approved for a two year Extended Mission #2 (EM-2), during which it will continue with its current unique suite of atmospheric science, plus take some new types of science measurements. From a Navigation standpoint, EM-2 will look very similar to the Primary Mission and EM-1. MAVEN will stay in its current nominal science orbit, with a few short "deep dips" into the lower atmosphere. The new science observations should have little impact on Navigation. It is expected that MAVEN will be requested to perform more relay support in EM-2 than previously, although it is likely to be minimal compared to the other orbiters to reduce the impact on science. After EM-2 though, MAVEN may be required to support much more relay work. MAVEN is also expected to support Mars2020 EDL and lander relay passes in 2021 and beyond. Some time after EM-2 MAVEN will plan to maneuver into a higher orbit. This higher orbit will reduced fuel usage and increase mission longevity and will help relay support via more accurate predictions (due to flying through less dense atmosphere). The nominal plan is to increase the periapsis altitude to ~230 km. However, desires to support Mars 2020 EDL support, provide better relay support geometry, increase mission longevity and achieve a satisfactory end of mission are part of continuing discussions of revisions to MAVEN's future plans. The current expectation is that MAVEN will continue in its nominal orbit through EM-2, with plans solidified near the end of EM-2 for the geometry of the rest of the mission.

XIII. Conclusion

The Navigation work over the first Mars year of science has been examined. The project requirements for Navigation accuracy, Navigation's pre-operations expectations of its accuracy, and the actual accuracies observed during operations have been compared. Navigation has met its reconstruction and prediction accuracy requirements. Additional information on prediction accuracies have been given which are relevant to COLA analyses and relay planning performed by Mars lander teams. The navigation team's experience with the atmosphere and its effects on prediction accuracies and corridor control has also been described. The navigation of the deep dips with their narrow density corridor and minimal density information can be difficult. Even though the first four deep dips went smoothly, deep dips 5-6 were more difficult due to the density behavior.

Acknowledgments

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