Navigation Design and Operations of MAVEN Aerobraking

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This paper describes the operational design and execution of the MAVEN aerobraking phase at Mars from a Navigation Team perspective. MAVEN was designed to perform atmospheric science in a ~150x6200 km altitude elliptical orbit. After the primary science mission, it was decided that MAVEN should circularize its orbit, as much as feasible from a spacecraft and mission standpoint, to better support relay operations with the landers. As a result, MAVEN performed aerobraking in the first half of 2019 to reduce its orbit to ~150x4500 km altitude. Although MAVEN did not decrease its altitude as low as previous aerobraking missions, it had several unique challenges. Science observations continued to be taken during aerobraking, requiring dramatically better Navigation accuracies than typical for such phases. Furthermore, continuous DSN coverage with 2-way Doppler data was not available. So, with 40% less Doppler data, Navigation had to meet prediction accuracies which were an order of magnitude smaller than in previous aerobraking operations. Spacecraft accelerometer data was included in Navigation analyses in order to meet these requirements.

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I. Introduction

The Mars Atmosphere and Volatile Evolution mission (MAVEN) is dedicated to the study of the Martian upper atmosphere and its evolution over time, examining its interactions with the sun and solar wind – particularly the loss of water and other volatiles to space [1]. MAVEN launched on 18 November 2013 and entered into orbit around Mars on 22 September 2014. The MAVEN primary mission lasted one Earth year, from 16 November 2014 to 15 November 2015. To get a wide range of information on the atmosphere, MAVEN had a 4.5-hour elliptical Nominal Science Orbit (NSO) with an apoapsis altitude around 6200 km and a periapsis altitude around 150 km [2,3]. MAVEN was approved for several extended missions, and continued taking science in the NSO up to February 2019.

The NSO was actually being flown in an average density corridor of 0.05 – 0.15 kg/km^3, with "Orbit Trim Maneuvers" (OTMs) being executed up to once a week to maintain that corridor. This resulted in the MAVEN periapsis altitude varying between 130 and 180 km. From an operations standpoint, this is very similar to a light aerobraking. To get additional density information, MAVEN would dip down into the atmosphere for a brief period. The density corridor was increased by an order of magnitude, to 2.0 – 3.5 kg/km^3, requiring MAVEN to reduce its periapsis altitude to around 125 km. These "deep-dips" (DDs) required intense daily aerobraking style operations and OTM capabilities, and used much more fuel. So only nine deep dips were performed during the mission. A deep dip typically lasted 9-10 days (for at least 5 days of science).

MAVEN's orbit inclination was 74.2 degrees*. Unlike Mars Global Surveyor (MGS), Mars Odyssey 2001 (ODY) and Mars Reconnaissance Orbiter (MRO), which were in sun synchronous orbits around Mars, the MAVEN orbit plane slowly rotated relative to the Sun. The orbit orientation also rotated within the orbit plane, resulting in periapsis varying between ±74 degrees latitude. The difference between the radius of the Mars equator and poles is 20 km. So, the MAVEN periapsis altitude would have varied by ±17 km if the MAVEN orbit was circular, or if the MAVEN periapsis radius from the center of Mars remained constant. However, the oblateness of Mars, specifically the Mars J3 gravity term, resulted in the periapsis altitude varying by approximately 55 km, with the minimum occurring when MAVEN is near the south pole and the maximum occurring when MAVEN is near the north pole. It took just over 15 months for the MAVEN periapsis to go through a full revolution in latitude – although this decreased to 8 months after aerobraking. In order to remain in the density corridor, this generally resulted in MAVEN needing to maneuver to lower altitudes as periapsis moved from the south toward the north pole to offset the naturally rising altitude. (And vice versa.) Of course, there were also significant atmospheric seasonal effects, along with latitudinal and regional effects, which could significantly change this generic maneuver expectation.

After the primary mission, the Mars Program Office (MPO) started working with the project on feasible options for future MAVEN operations within the network of NASA Mars missions. The key requirements on MAVEN which came out of this work were:

- MAVEN shall support the NASA Mars 2020 (M2020) Entry, Descent and Landing (EDL).
- MAVEN shall reduce its apoapsis altitude to 4000-4500 km by the time of M2020 EDL.
- MAVEN shall have enough fuel to last to 2030.

In order to reduce MAVEN's apoapsis altitude and still have enough fuel to last to 2030, aerobraking was required. However, the MAVEN spacecraft was not designed for aerobraking. After a comprehensive analysis, it was determined that MAVEN could perform a shallow aerobraking at its typical deep dip altitudes with acceptable risks to the spacecraft and science instruments, and that this would be sufficient to accomplish the required apoapsis altitude reduction. This paper will discuss the operational design and execution of aerobraking. A companion paper, *MAVEN Orbital Trajectory Analysis: Design and Implementation of Lander Relay Support*, [4] will concentrate on the overall design of the Maven trajectory to meet the above requirements on MAVEN, including the resulting options and constraints that this levied on aerobraking.

II. Comparison Between the MAVEN Mission and General Aerobraking

Historically, aerobraking has been a fuel-efficient alternative to a maneuver for reducing the size of the spacecraft orbit. The main purpose is to modify the trajectory, with no requirements for the support of science. This would be accomplished by using drag passes through the atmosphere to reduce the apoapsis altitude. A density corridor or limit would be defined which would satisfy spacecraft safety, yet still allow the final post-aerobraking orbit to be achieved at the desired time. Daily operations would be required, with the capability of frequent quick maneuver decisions and executions. This is described in detail in multiple papers about the aerobraking of previous Mars missions (MGS [5-7], ODY [8], MRO [9-11]).

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* After the inclination change maneuver (ICM-1) on 25 July 2018, the inclination was increased to 74.9 degrees.

The nominal MAVEN science mission can be described as a light aerobraking mission with atmospheric science. Several aspects of operations were similar to aerobraking, and many operations processes were derived from previous aerobraking experience. Two key examples are the control of the trajectory and the method of meeting the spacecraft down-track timing (position) accuracy.

As mentioned above, MAVEN nominal operations required controlling the periapsis density within a specific corridor. This was the same as for aerobraking – except the MAVEN corridor was at much smaller densities. The OTM process used to maintain MAVEN in the corridor was exactly the same as in aerobraking, allowing for quick OTM decisions and executions. A "menu" of maneuver size magnitudes, or ΔVs, were pre-defined for all OTMs. This allowed those sequences to be created and validated before MAVEN got into orbit around Mars. The OTM was executed at apoapsis either along or opposite to the spacecraft velocity vector, or in the "up" (increase in periapsis altitude) or "down" (decrease in periapsis altitude) direction. Those "maneuver pointing" sequences could also be validated before orbit operations. Thus, to specify an OTM, all that was needed was to give the apoapsis orbit number, the direction ("up" or "down"), choose the ΔV from the menu, and then use the appropriate pre-validated OTM sequences. This maneuver process and ΔV menu were used for all MAVEN corridor control maneuvers. The only difference was in the naming, where they were called OTMs (Orbit Trim Maneuvers) in the nominal science corridor, DDMs (Deep Dip Maneuvers) in the deep dips, and ABMs (Aerobraking Maneuvers) during aerobraking. The frequency at which the maneuvers could be executed was determined by the frequency needed to keep MAVEN within the desired corridor – and the DSN tracking pass schedule. OTMs could be executed once a week, while DDMs could be executed daily and ABMs generally three times a week.

For spacecraft flying through the atmosphere, the error in the predicted spacecraft down-track position, or its location within its orbit, grows very quickly.[*] (This is typically expressed as a timing error.) This causes significant difficulties in the ability to predict spacecraft down-track positions accurately enough for mission requirements. During previous aerobraking missions, Lockheed-Martin (LM) developed the "Periapse Timing Estimator" (PTE) software on their spacecraft to estimate the effects of each drag pass, and add appropriate corrections to the Navigation Team down-track position predictions [12]. This enabled the spacecraft to meet the typical aerobraking 225 second down-track timing requirement over many orbits. However, one of the main differences between MAVEN and historical aerobraking is the support of atmospheric science. As a result, the Navigation down-track timing accuracy requirement is 20 seconds – an order of magnitude less than typical aerobraking. Thus, an enhanced version of PTE was developed for MAVEN. The sequence architecture on MAVEN was designed to enable PTE to control the timing of most of the spacecraft and science sequencing.

Although MAVEN continued to support science and the 20 second requirement during its aerobraking, the aerobraking was significantly simpler than for the previous Mars orbiters for a couple of reasons. It was not constrained to a particular solar time of the ascending node at the end of aerobraking, so it did not have to fly on a specific "glideslope" defining its aerobraking mission. It only had to fly ahead of a limiting glideslope which defined a hard aerobraking end date. Since MAVEN did not use aerobraking to fully circularize its orbit, it did not have to worry about operations in very short orbit periods. Such orbits tend to increase and intensify operations, shorten work schedules, create additional complexity due to spacecraft lifetime concerns (i.e. prevent the spacecraft spiraling down into the planet due to the atmosphere), and complicate "collision avoidance" or COLA analyses. (See section VIII and Ref. [11].) Finally, since MAVEN had incorporated many aerobraking-type processes in its operations from the start, and since each of the previous nine deep dips was like a mini aerobraking, Navigation personnel were well prepared for aerobraking operations. In previous Mars missions, aerobraking started soon after insertion into orbit, before the mission teams had much experience with operating the spacecraft in orbit.

III. MAVEN Aerobraking Operations Plans

The MAVEN aerobraking would reduce the apoapsis altitude from 6200 km to approximately 4500 km, and reduce the orbit period from 4.5 to 3.6 hours. After additional analyses within the MAVEN project, it was determined that the potential effects on the spacecraft and science instruments of aerobraking for an extended time at deep-dip densities were acceptable. However, since MAVEN does not have an articulating High Gain Antenna (HGA) and has fixed solar panels, smaller orbits lead to greater spacecraft power constraints, especially during periods when a solar eclipse takes up a significant portion of the MAVEN orbit. MAVEN's required relay support during the Mars Insight lander checkout and validation period constrained when MAVEN could start aerobraking. Furthermore, in order to have enough fuel to last to 2030, aerobraking was also being used as a "free large

[*] For MAVEN, the angular momentum desaturations were performed on balanced thrusters. There was one desaturation per orbit, but its total ΔV was negligible (and often not detectable) relative to the drag pass perturbation.

maneuver" to help synchronize MAVEN for its support of the Mars 2020 EDL. Accounting for all of these restrictions, and getting some relaxation on the Insight support, the MAVEN aerobraking period was constrained to be within 11 February – 10 May 2019. Aerobraking at the previous deep-dip densities would allow MAVEN to finish within this aerobraking period with little margin. So, the deep dip corridor was expanded to an aerobraking average density corridor of 2.0 – 5.5 kg/km^3, with the desire to stay closer to the high-density region. (This is still nearly an order of magnitude less than the ODY and MRO aerobraking corridors [8-11].) This would give more margin in case of a contingency, giving MAVEN a much better chance of finishing aerobraking within the limited time period, meeting its apoapsis altitude requirement, and being able to support Mars 2020 EDL.

A. Aerobraking Glideslope

A reference trajectory was generated in October 2018 which used this aerobraking for M2020 EDL targeting. The aerobraking in that reference trajectory was conservative, ending on 3 May – a little before the 11 May hard end date limit for aerobraking. So, this was used as the "reference" for flying the MAVEN aerobraking. For the previous MGS, ODY and MRO missions, aerobraking was used to hit specific trajectory targets and dates [5-11]. Thus, each mission had a reference trajectory that it tried to keep close to. However, MAVEN was able to use its reference trajectory in the much less constrained manner of a "limiting glideslope."

The only constraints MAVEN had was to support M2020 EDL and lower the apoapsis altitude to 4000-4500 km. The 500 km range in altitude was given to allow MAVEN the flexibility to efficiently target M2020 EDL via aerobraking with a minimal use of fuel. The October 2018 reference trajectory showed that M2020 EDL would be adequately targeted with an apoapsis altitude at the end of aerobraking of 4522 km. So, this was used as MAVEN's initial target. However, ending aerobraking early does not have a significant penalty on the M2020 EDL targeting, and gives much desired margin for dealing with possible contingency situations. Thus, unlike the other missions, the MAVEN reference trajectory was used as a limiting glideslope instead of a targeting glideslope. In other words, MAVEN could fly aerobraking as fast or faster than the reference glideslope, but would be in trouble of meeting its MPO requirements if it flew slower than the glideslope. A sample trajectory was generated with aerobraking ending on 12 April. It was considered more realistic of what MAVEN would actually be attempting to fly.

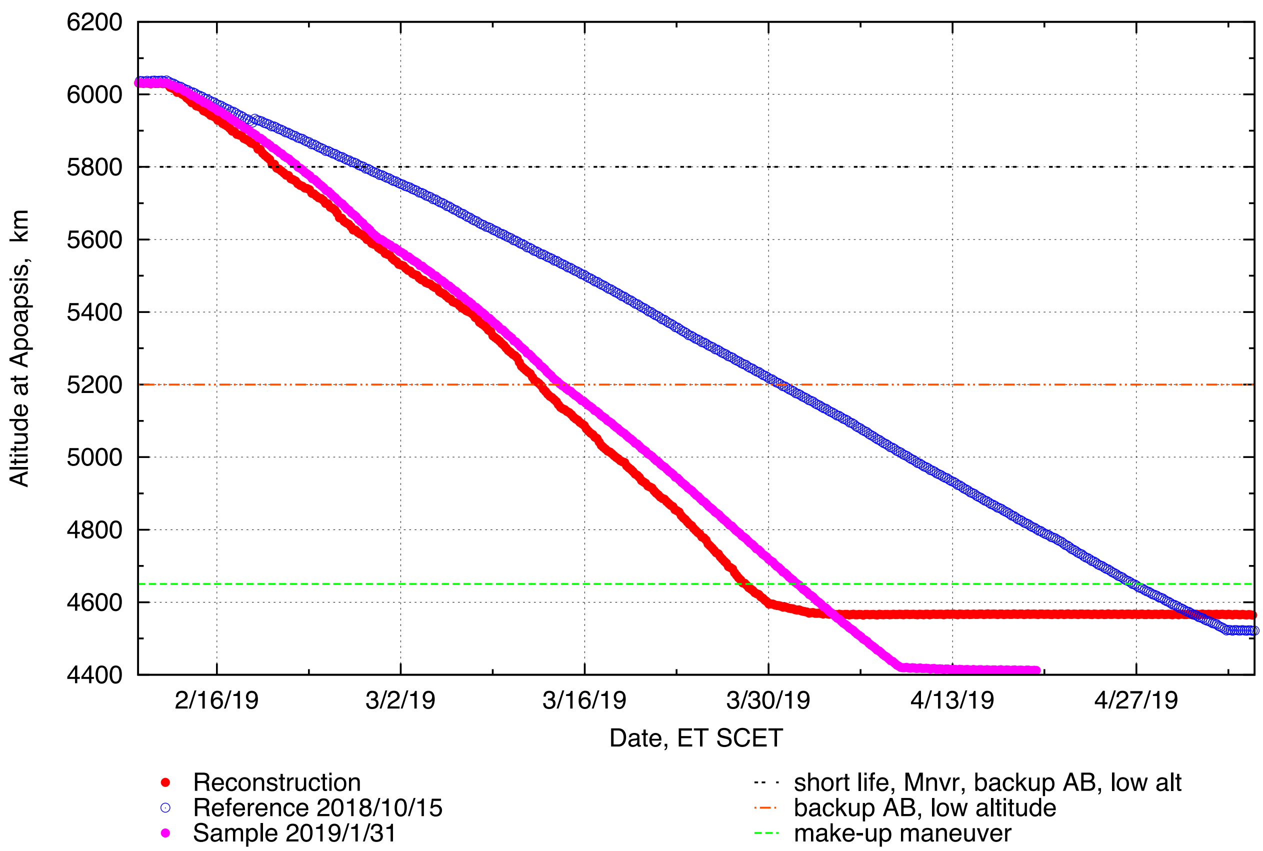

Fig. 1: Aerobraking apoapsis altitude glideslopes.

Figure 1 shows the aerobraking apoapsis altitude glideslope for the reference trajectory, the sample trajectory, and the actual aerobraking. It shows that MAVEN was able to keep substantially ahead of the limiting glideslope (blue curve). As a result, in mid-March a quick analysis was performed to determine how much, if any, the ending aerobraking apoapsis altitude target should change for targeting M2020 EDL. From this work, the ending apoapsis altitude target was changed from 4522 km to 4560 km. It was considered very good if the project could achieve that target to within ±10 km, and even larger discrepancies could be handled if necessary. The achieved post aerobraking apoapsis altitude was 4566 km.

The horizontal lines in Fig. 1 denote key benchmarks for contingency situations. If MAVEN aerobraking did not reach an apoapsis altitude of 5800 km (grey line), then MAVEN could not support M2020 EDL. It would also end up at a much higher apoapsis altitude than desired by the Mars lander relay assets. At less than 5800 km MAVEN could only support M2020 EDL if it executed a large propulsive maneuver, an aggressive aerobraking during a later short backup opportunity, and dramatically reduced its mission lifetime. If MAVEN aerobraking reached 5200 km (orange line), then M2020 EDL could be supported without a significant reduction to mission lifetime. However, another aggressive aerobraking campaign would have to be executed during one of the later short backup opportunities. Also, the ending apoapsis altitude would be much lower (e.g. 4000-4300 km, to achieve the targeting for M2020 EDL), which would be worse for MAVEN science. Finally, if MAVEN could get down to approximately 4560 km (green line), a propulsive maneuver could be executed to move MAVEN's apoapsis altitude down the rest of the way and support M2020 EDL.

B. DSN Tracking Coverage

In the past, aerobraking had required continuous 2-way DSN support – as did the MAVEN deep dips. Unfortunately, continuous DSN 2-way coverage was not possible during the MAVEN aerobraking period. Navigation and the project performed some further analyses and operations modifications, and decided that a reduction in tracking of nearly 40% could be taken with acceptable risks.[*] To support this reduced tracking, the MAVEN aerobraking operations was changed to that of a typical deep dip (and aerobraking) daily operations schedule for Monday, Wednesday and Friday with continuous 2-way tracking being required over 24 hours. On the other days MAVEN requested an 8-hour DSN pass of 2-way support. This meant that the project had only three Aerobraking Maneuver (ABM) opportunities per week, at the end of Monday, Wednesday and Friday. (OTM was renamed as ABM during aerobraking.) This limitation was considered acceptable for MAVEN's specific aerobraking situation, with the important exception of continuous DSN coverage and daily ABM opportunities for the first week of aerobraking (for walk-in and Phobos collision avoidance).

The single 8-hour DSN pass on the other days allowed the project to download telemetry from the spacecraft, and upload commands if necessary. These passes were important for contingency scenarios, such as working around a "red" (non-operational) DSN antenna. They also enabled telemetry from the spacecraft to be downloaded more frequently for detailed health and safety checks. For Navigation, it allowed reconstructed spacecraft attitude, momentum desaturation, and accelerometer information to be downloaded. This was very useful as it allowed Navigation to perform timely reconstruction of the trajectory, which enabled a detailed history of density information, key to the models and OTM/ABM decision incorporated into the upcoming Navigation prediction delivery.

The non-continuous Doppler would have resulted in limited drag-pass density history information, and Navigation trajectory reconstruction accuracies dramatically larger than science required. However, Navigation created an efficient process for including simplified accelerometer-based measurements into its orbit determination filter. (See section VI.) This solved both of the above problems. Considering the many spacecraft that the DSN now supports, it is doubtful that continuous DSN support will be feasible for any future NASA aerobraking mission.

Since the DSN scheduling is done so far in the future, one does not know beforehand where the periapses, occultations, and uplink constraint periods will fall within a 24-hour continuous DSN period. So any gap in the continuous tracking could potentially break the operations for that day and, in the worst case, force the project to wait 2-3 days for another ABM opportunity and fly at potentially dangerous densities. The project pushed hard to get the required continuous tracking periods, and was largely successful. In the very few cases where there were potential problems (either due to scheduling or "red" stations), the density behaved well so an ABM was not required. The project had significantly more trouble getting the single 2-way DSN pass on the other days. It was almost always significantly less than 8 hours, and a few times there was no pass at all. Luckily, there was no case

[*] Since MAVEN does not have an ultra-stable oscillator, Navigation requires 2-way X-band Doppler.

when there was a day with a problematic (or missing) single pass which was needed for a contingency situation due to spacecraft or DSN problems – or unexpected density behavior.

Unlike during the deep dips, spacecraft telemetry data was downloaded near the beginning of the 24-hour continuous DSN segments. Although that sacrificed some science, that was very important with the poor single pass support on the other days, and allowed Navigation (and the Spacecraft Team) to use the accelerometer data to help fill in missing recent density information, resulting in better informed ABM decisions.

C. Operations Schedule

As described above, much of the MAVEN operations were already largely setup to support aerobraking, especially from a Navigation standpoint. Monday, Wednesday and Friday, with their 24 hours of continuous DSN coverage, were the main days of operational work, and were executed just like normal deep dip operations days. Navigation used the first 3-4 orbits of the DSN tracking to perform orbit determination and get an estimate of the current density behavior, which was used to generate a prediction model for the density. Then Navigation performed some analyses on ABM options. This was followed by analyses of possible COLA situations. (See section VIII.) This was folded into an ABM recommendation to the project. An ABM project decision meeting followed. The decision was included in the Navigation predicted trajectory, which was then delivered to the project. The Spacecraft Team (SCT) then converted the trajectory and ABM (if appropriate) to upload products for the spacecraft. These products, along with other upload sequences, were sent to the spacecraft while its High Gain Antenna (HGA) was earth pointed towards the end of this 24-hour continuous tracking period. The ABM was executed at apoapsis, after all uploads and downloads were completed. This schedule was driven by the need to upload the new ephemeris onto the spacecraft before the third Navigation predicted periapsis in order to satisfy the 20 second science prediction accuracy requirement on Navigation. Once onboard, PTE could keep the predicted accuracy within 20 seconds. (Due to the decreasing orbit period, this had to be increased to four periapses midway through aerobraking in order to give Navigation and the SCT enough time to perform all necessary work.) As can be seen, this 24-hour period of DSN tracking and operations work was intensive, with little flexibility for contingencies or gaps in DSN coverage.

IV. Aerobraking Execution

Navigation used Mars-GRAM 2005 with the Map Year 0 model as the base Mars atmosphere model from the NASA Marshall Space Flight Center as its reference density model [13,14]. (From now on it will simply be referred to as Mars-GRAM or MG.) Aerobraking started after the dust storm seasons, so the atmosphere was expected to be relatively calm. There was the potential for MAVEN to cross into the southern polar vortex near the end of the aerobraking period, which could have increased density variability and degraded density predictability. However, MAVEN finished aerobraking early, thus avoiding this region. The density remained relatively consistent and constant throughout the actual aerobraking. As a result, MAVEN was able to perform aerobraking with only three corridor-control ABM's (two of which could have been skipped). The Navigation estimates of density for each drag pass were used to derive prediction models and assist in ABM decisions. Atmosphere Advisory Group meetings were held at least twice per week to advise on the current state and near-future trending of the Mars atmosphere.

Aerobraking used only 6.734 kg of fuel, or equivalently 14.8 m/s of ΔV. If this orbit change had been performed via a propulsive maneuver, approximately 102 m/s would have been required. Thus, this aerobraking saved 85% of the fuel that would have been required for a propulsive maneuver. That converts into an additional seven years of relay support for Mars landers in the higher MAVEN science relay orbit (SRO) after M2020 EDL.

A. Aerobraking Summary

From a Navigation standpoint, aerobraking lasted from 11 February to 3 April 2019, taking 51 days or 325 orbits (orbits 8535-8840).[*] The walk-in took 0 days, with 46 days in the aerobraking corridor and 5 days for the walk-out. Aerobraking started on 2019-02-12 01:30 UTC with the maneuver ABM-1A at the apoapsis of orbit 8534 (A8534). Aerobraking ended with ABM-8B at A8840 on 2019-04-04 01:39 UTC – over a month earlier than the hard limit for ending aerobraking. (From a spacecraft configuration standpoint, aerobraking started on 2019-02-11 and ended on 2019-04-05 UTC.) The first walk-out maneuver was on A8807 at 2019-03-30 00:35 UTC. Thus, 46 days or 272 orbits (8535-8807) were spent in the aerobraking corridor. Due to the DSN coverage limitations, walk-out ABM's could only be executed on Monday, Wednesday and Friday. Thus, it took five days (33 orbits) and three ABM's (ABM 7C, 8A, 8B) to walk back into the nominal science corridor. A total of only 8.9 m/s were used for maneuvers

[*] Orbits are counted from periapsis. The periapsis during Mars orbit insertion is defined to be orbit 1.

during aerobraking: 3.0 m/s for walk-in; 0.8 m/s for corridor control; and 5.1 m/s for walk-out. Thus, only 6.74 kg of propellant was used out of a budgeted 12.5 kg.

Aerobraking occurred in the southern hemisphere, with the periapsis latitude traveling from -5.7 to -52.2 degrees.

MAVEN was targeting an apoapsis altitude of 4560 km. This value was determined by the desire to use aerobraking as a “free maneuver” to synchronize MAVEN’s orbit with Mars 2020 EDL on 18 February 2021. The EDL targeting was not that sensitive to the ending apoapsis altitude, and the actual final apoapsis altitude was 4566 km. The total reduction in the apoapsis altitude from aerobraking was 1464 km, from 6030 km to 4566 km. Due to drag, the apoapsis altitude is expected to be under the 4500 km requirement before the time of the Mars 2020 EDL. The orbit period was reduced from 4.41 hours to 3.67 hours. In terms of drag effects on the orbit, the apoapsis altitude was reduced by approximately 5 km per orbit, and the period was reduced by approximately 10 seconds per orbit. The eccentricity decreased from 0.455 to 0.385.

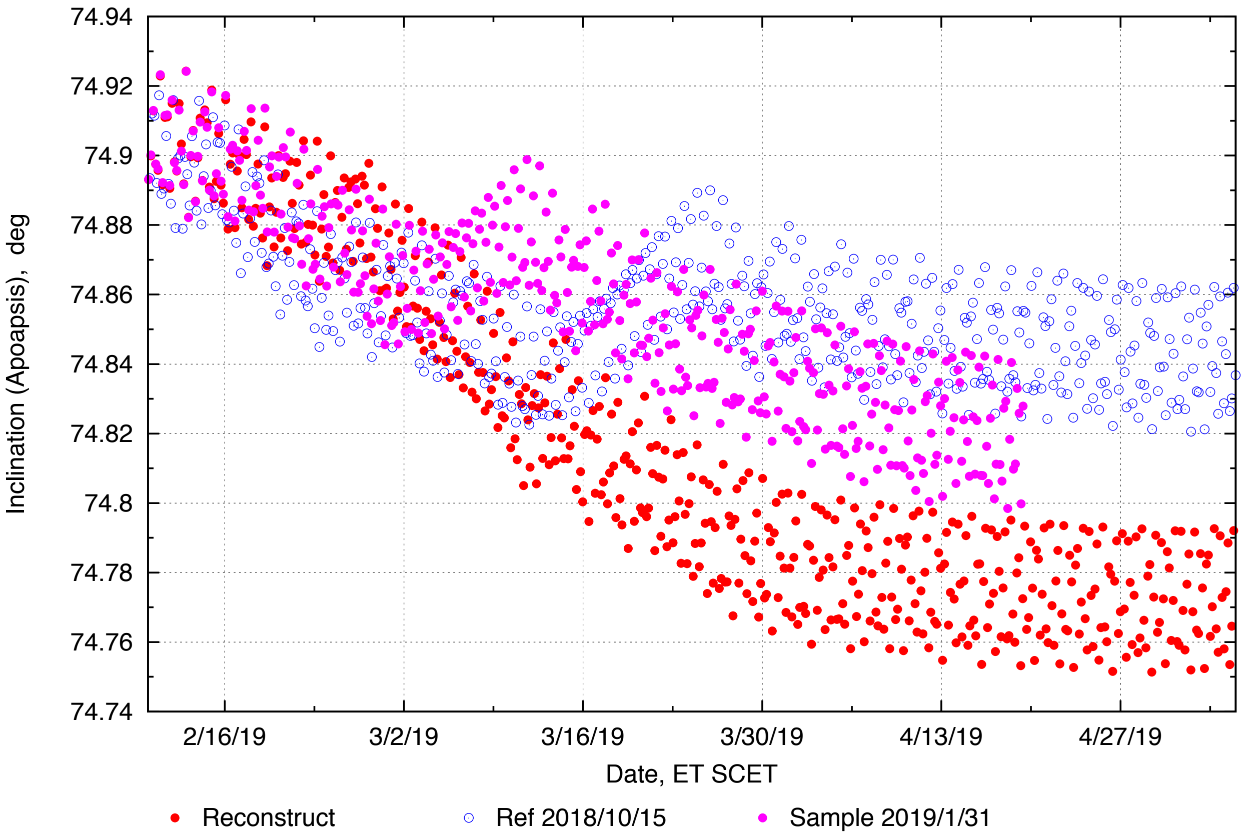

Fig. 2: Changes in inclination around orbit resonance during aerobraking.

A 6-orbit resonance (ground track repeat cycle) occurred around March 6. This resonance can perturb the inclination, but is hard to predict. Significant perturbations in the inclination were observed in the preceding reference and sample trajectories, as shown in Fig. 2. However, the inclination perturbation in the actual MAVEN trajectory was minimal. Such inclination changes could affect the Mars 2020 EDL targeting, but enough margin was built into the EDL targeting design to allow for the variation seen in this figure.

Aerobraking occurred in the southern hemisphere above the polar vortex, with the periapsis latitude traveling from -5.7 to -47 degrees, decreasing to -52.2 degrees by the end of the walk-out (Fig. 3). The periapsis altitude, consistent with the density corridor, started at 133 km and ended at 125 km. The solar longitude, Ls, went from 339 to 3 degrees. The true local solar time of periapsis went from 22.4 to 17.6 hours (or from near midnight to just past the terminator).

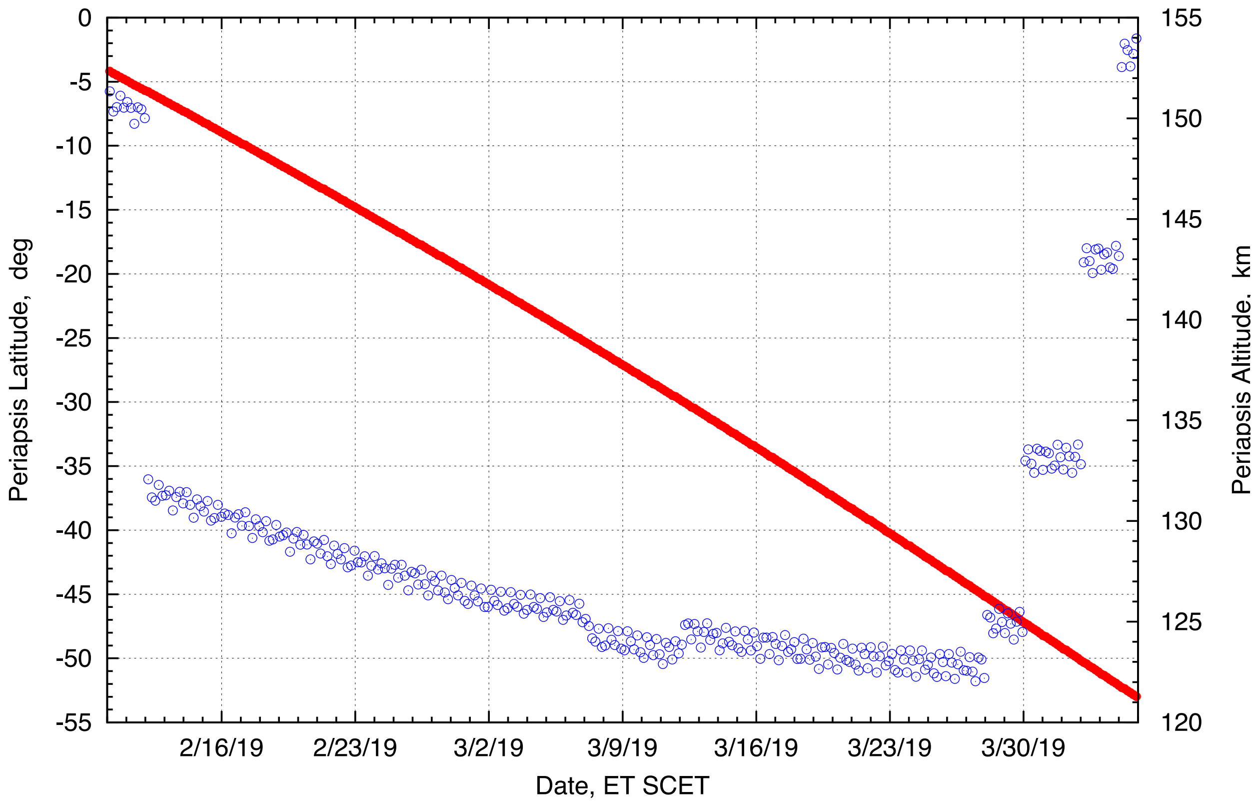

Fig. 3: Aerobraking geometry: periapsis altitude (blue) and latitude (red).

B. Aerobraking Maneuvers and Corridor Control

MAVEN had nearly continuous DSN coverage for the first week of aerobraking. This was to support daily ABM opportunities for walking into the aerobraking density corridor, and to allow MAVEN to avoid potential multiple Phobos COLA situations during its 15-17 February COLA season. (See section VIII.) For ABM-1A, the project chose a -3.0 m/s (down) ABM-1A on A8534. The maneuver decreased the periapsis altitude by 18.6 km, resulting in a predicted increase in density from approximately 0.16 kg/km^3 to 1.5 kg/km^3. This translates into an effective density scale height of 8.3 km from the Mars-GRAM model. The actual post-ABM densities were near 3 kg/km^3, resulting in the actual scale height being around 6.5 km. Thus, the walk-in to aerobraking unexpectantly took only one maneuver. Note that the Mars-GRAM and actual density scale heights converged towards each other as aerobraking progressed. By the end of aerobraking, the Mars-GRAM predicted post-ABM densities were close to the actual ones.

It was fortuitous that ABM-1A (2019/02/12 01:30 UTC) put MAVEN directly into the aerobraking density corridor since that helped the project work around several DSN station problems at the beginning of aerobraking. The DSS-14 antenna was "red" (no uplink capability) early on 11 February UTC (Day Of Year 042), which was the nominal pass scheduled for designing ABM-1A. However, Nav was able to use a previous DSN pass without significant concern, since ABM-1A would not be targeting the aerobraking corridor and further walk-in maneuvers were anticipated. Fortunately, ABM-1A put MAVEN right in the corridor. On the following day DSS-25 was "red". It had been planned for that day's uplinks to the spacecraft – including ABM-1B. Since MAVEN was already in the corridor, some last minute changes to that days operations schedule were able to be implemented and ABM-1B was cancelled. There were a few other cases of red DSN stations during the first 1-2 weeks of aerobraking which affected ABM decisions (e.g. ABM-2A) and/or shifted work schedules. However, the density remained around 3 kg/km^3, nicely in the aerobraking corridor, resulting in these DSN problems having no significant impacts on MAVEN. Also, MAVEN was fortunate in that, after ABM-1A, its nominal trajectory avoided all potential COLA concerns with Phobos. After these first couple of weeks, MAVEN experienced very few DSN problems.

In the first part of aerobraking, the periapsis latitude was decreasing from near the equator towards the south pole. As previously mentioned, the oblateness of Mars resulted in the periapsis altitude naturally decreasing during this time. Mars-GRAM predicted that the density would remain constant at a constant altitude. So, the project was expecting to need to perform a few "up" ABMs (to a slightly higher periapsis altitude) to remain in the corridor. However, the density was actually slightly decreasing at a given altitude. This slight decrease balanced out the decreasing periapsis altitude, resulting in the density remaining around 3-4 kg/km^3, thus requiring no ABMs.

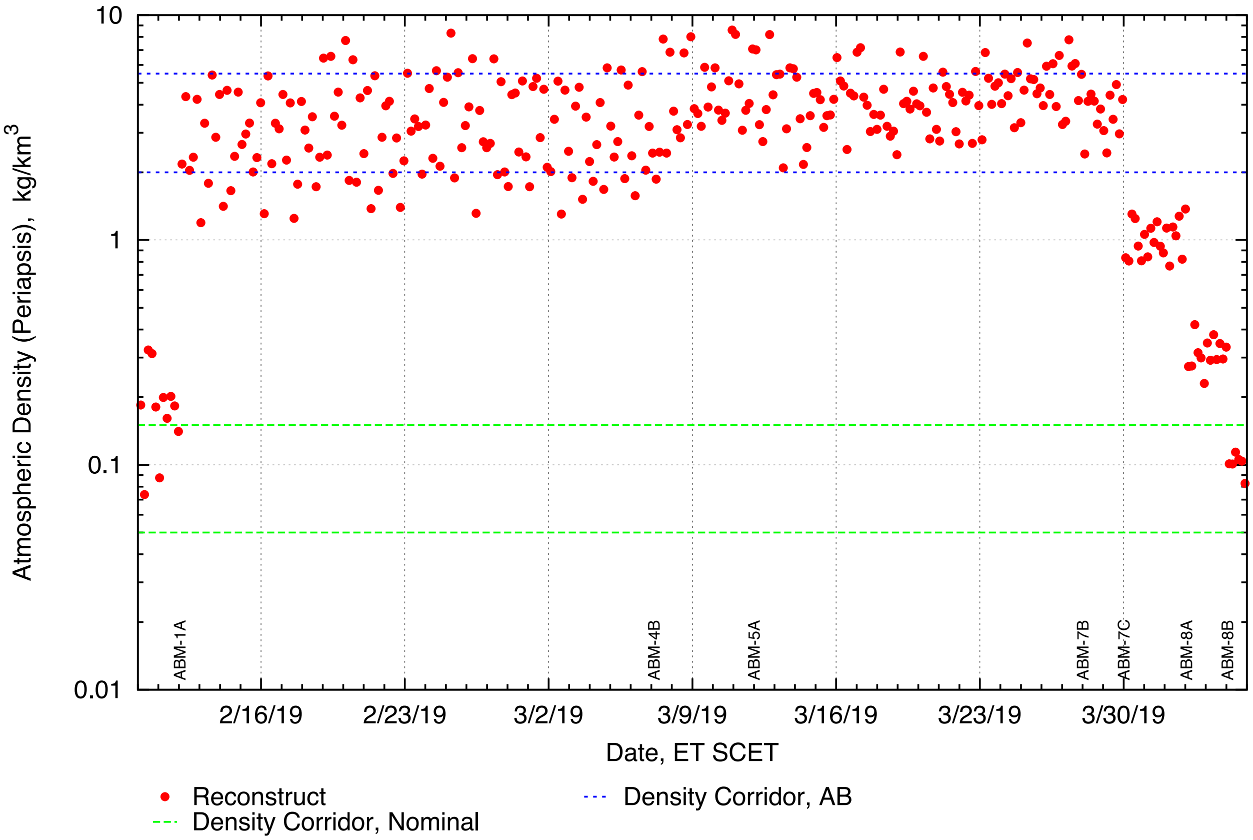

Fig. 4: Aerobraking density profile, including walk-in, walk-out and the maneuvers. The nominal science corridor is defined by the green horizontal lines, whereas the aerobraking corridor is defined by the blue lines.

Although it was not required, a small ABM-4B was executed in the middle of aerobraking, at 2019/03/07 03:38 UTC (A8665). The density looked like it was moving lower, getting down near 3 kg/km^3, and had been stable. The project wanted to keep a healthy margin in their aerobraking schedule to guard against contingency situations, as previously mentioned. Thus, it seemed like this was an appropriate and safe time to aerobrake slightly more aggressively. The -0.2 m/s (down) ABM-4B was expected to move the mean density up to 3.3 kg/km^3. Unfortunately, after ABM-4B the density started increasing. By the time of the ABM-5A decision, nearly a week later, it had reached 5 kg/km^3. So a small +0.2 m/s (up) ABM-5A was executed at 2019/03/12 00:27 UTC (A8694) to bring the mean density down to 4.7 kg/km^3.

The AB walk-out had complications. Navigation was trying to target an apoapsis altitude of 4560 km at the end of AB, while trying to avoid potential COLA concerns during the MEX and MRO COLA seasons. (See section VIII.) The +0.4 m/s (up) ABM-7B at 2019/03/28 00:39 UTC (A8794) was technically a corridor control maneuver. It was performed to: move the density away from the edge of the corridor – from 5 kg/km^3 (with some orbits having very large values) to 3.7 kg/km^3; allow the project to get an estimate of the actual density scale height before the large walk-out maneuvers; and to give better control for the targeting of the ending 4560 km apoapsis altitude. The densities after ABM-7B were as predicted, implying that the density scale height was consistent with the Mars-GRAM predicted 7.2 km scale height.

The first walk-out maneuver was performed with a +1.5 m/s ABM-7C at 2019/03/30 00:35 UTC (A8807). This was half of the total DV required for walk-in. It would get MAVEN down to significantly smaller densities (1.3 kg/km^3), yet have plenty of margin since there are large atmosphere uncertainties with this large of an altitude change (8.3 km). Also, it would give information on the density scale height, which would be important in choosing the following walk-out maneuvers to get into the NSO corridor. Another important aspect of the design was that ABM-7C would dramatically reduce the rate of decrease in the apoapsis altitude. So, it was important to pick an ABM size which got MAVEN near to the 4560 km apoapsis altitude target. The densities after the ABM-7C were around 1.0 kg/km^3, slightly smaller than the predicted 1.25 kg/km^3. A +1.8 m/s (up) ABM-8A was executed at 2019/04/02 01:59 UTC (A8827), which was predicted to move the density to 0.32 kg/km^3. This gave some margin since the actual densities after ABM-7C seemed to imply a slightly smaller scale height than Mars-GRAM had predicted. The post ABM-8A densities were as predicted, so a +1.8 m/s ABM-8B was executed at 2019/04/04 01:39 UTC (A8840) to put the density into the middle of the nominal science corridor (near 0.1 kg/km^3, with a predicted scale height of 9.5 km). After Navigation validated that the actual densities after ABM-8B were around 0.1 kg/km^3, the Spacecraft Team reconfigured MAVEN for nominal science operations on 5 April 2019.

Note that only 3.0 m/s was used for the walk-in, whereas 5.1 m/s was used for the walk-out. This was partly due to the larger altitude and density change during the walk-out (a 28.3 km altitude increase for a density decrease from 5.0 to 0.11 kg/km^3 for walk-out, versus an altitude decrease of 18.6 km for a density increase from 0.17 to 3.0 kg/km^3 for walk-in), and partly due to the larger density scale height (~8.2 km for walk-out versus ~6.5 km for walk-in).

V. Aerobraking Orbit Determination and Prediction Accuracies

The modeling of the density was by far the largest error source. There were two parts to this modeling error: the bias error in the mean density, and the orbit-to-orbit density variation. The bias error was the major error source of the two, except for the first few orbits. Navigation used the Mars-GRAM, and corrected it via a “density scale factor” (DSF) with which to multiply the Mars-GRAM density. The DSF was estimated for every orbit, with a constant DSF used for the predicted densities. By looking at the past history of the estimated or reconstructed DSF’s, a value for the predicted DSF was chosen. Thus, in order to determine an accurate value for the predicted DSF, it was important to have good reconstructed DSF estimates for all orbits up to the time of the analysis. In terms of estimating the Navigation prediction accuracy, a 3-sigma 40% error was assumed for the bias DSF,[*] and a 105% error was assumed for the stochastic (orbit-to-orbit) DSF.

Since the AB corridor covers higher densities than the DD corridor, Navigation’s ability to meet the prediction requirement was uncertain. From covariance analysis, at the start of aerobraking, Navigation could almost meet its 20 second 3-sigma orbit timing prediction accuracy requirement for science by the time of the ephemeris upload to the spacecraft – i.e. after three orbits of prediction in the first half of aerobraking. The ability to meet this requirement degraded as the orbit period decreased. In the latter half of AB, due to operations work schedule constraints, the new Navigation ephemeris could not be uploaded till right before the fourth periapsis, at which time PTE could “take over” and control the down-track timing accuracy. Unfortunately, Navigation could not come close to meeting the 20 second 3-sigma requirement after four orbits. The main purpose of aerobraking, though, was to reduce the apoapsis altitude. So, although highly desirable science could be taken during aerobraking, it was of secondary importance. Also, based on tracking Navigation’s actual prediction accuracies during the previous deep-dips, Navigation expected that it would meet the 20 second accuracy requirement for most if not all predictions. Post-aerobraking analyses (Fig. 5) showed that Navigation did meet this requirement for all predictions.

Since MAVEN does not have an ultra-stable oscillator, two-way Doppler (from now on simply called Doppler) had been the only data used in Navigation orbit determination analyses.[†] If continuous DSN coverage was available, quality estimates for the DSF of every drag pass could be derived. Without continuous coverage, as was the plan for MAVEN’s aerobraking, one might not be able to get good DSF estimates for every orbit (depending on the tracking coverage gaps), the reconstructed trajectory accuracies would dramatically degrade and violate the project requirements, and the ability to make good ABM decisions would be degraded. Since MAVEN was taking significant science during aerobraking, unlike previous missions, the degraded reconstruction accuracies were important. However, the use of accelerometer data in the orbit determination allowed atmospheric perturbations to be reconstructed for all orbits, thus allowing Navigation to easily meet the 3 km trajectory reconstruction requirement.

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[*] Due to the more limited DSN tracking and Doppler available to MAVEN compared to previous Mars orbiters, the MAVEN 3-sigma bias density error had been increased from 30% to 40%.

[†] Two-way range had no significant benefits for Navigation in the MAVEN orbit, and would have complicated the Navigation analyses. Plus, it would have reduced the length of MAVEN’s DSN station tracking passes due to the increased setup time required. The project was often struggling to get a minimal DSN schedule as it was.

There had been several previous attempts to include accelerometer data in Navigation orbit determination. However, none of them were successful enough to be confidently used operationally – largely due to the accelerometer data “fighting” the density profile defined by Mars-GRAM. Navigation fell back to a process of using simple derived information from the accelerometer data to define “accelerometer” parameters for use in the Navigation filter, as described in the next section. This process, which was partially tested during the ExoMars Trace Gas Orbiter (TGO) aerobraking [15], was incorporated into the official Navigation software for MAVEN aerobraking, and proved very successful. It also added little overhead to the nominal Doppler filter runs. As long as Navigation was able to get the accelerometer data downloaded from the spacecraft in a timely manner, this data could be used to resolve all of the problems of non-continuous DSN coverage. To ensure this, the accelerometer data was downloaded at least daily during aerobraking, including a download near the start of the 24-hour continuous DSN tracking periods.

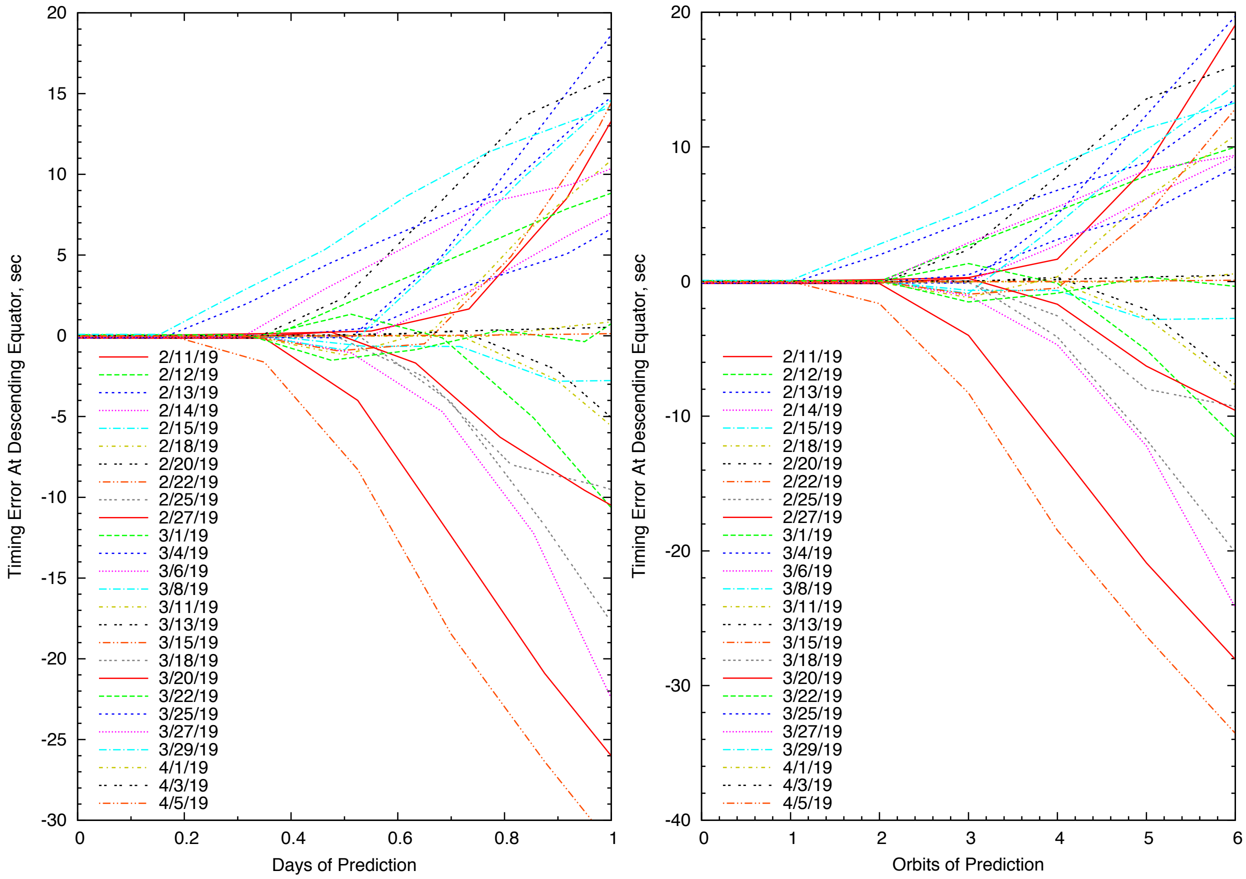

Fig. 5: Navigation down-track prediction accuracy during aerobraking.

VI. Navigation Use of Accelerometer Data in Orbit Determination

In order to continue to meet Navigation reconstruct accuracy requirements with the reduced tracking schedule, on-board accelerometer data were downlinked and integrated into the orbit determination process, as detailed in a previous paper [16]. The accelerometer data throughout a drag pass were collected, and accumulated into a single ΔV vector that was then included in the filter. This accumulated ΔV contains the most valuable information, with only the high-rate variability being lost (which has no direct impact on the trajectory), and has a much wider region of convergence than high-rate acceleration values. In addition to the vector data, the time centroid was also computed and included in the filter. It was the time at which the effective impulse was applied, and was derived by fitting the accelerometer data to a centroid and finding the time of its peak. This time shift in the applied drag ΔV, usually approximately ±1 minute, has an order of magnitude smaller effect than the variation in the drag, but the effect is still significant with the large drag ΔVs observed during aerobraking.

The ΔV values were weighted at 0.5 m/sec (1σ), a value determined by comparing Doppler-based estimates of pre- and post-periapsis orbital periods, which are significantly more accurate, with the calculated accelerometer data. The centroid times were weighted at 5 seconds. These values gave observability to parameters that are not included in the baseline Doppler density scale factor estimate, which only allowed modeling of the total down-track ΔV. Therefore, an impulse with cross-track and radial terms were added at each periapsis, representing the unmodeled lift and sideslip terms, and weighted at 5-10% of the nominal ΔV. The fact that the peak drag is often offset from the nominal, leading to an offset in the time of the effective ΔV, was modeled using equal and opposite down-track ΔV before and after periapsis, weighted to a value equivalent to a time offset of 30-60 seconds.

The effects of this are significant. When multiple periapses are included in a gap between Doppler passes, the only information about drag during that time frame is the change in orbital period and periapsis time, which are function of the drag ΔVs, and to a lesser extent the effective time of those ΔVs. Considering the simple case of down-track ΔV only, there are two constraints and a variable number of ΔV values, based on the length of the gap relative to the orbital period. If only two periapses are within the Doppler gap, this is a well determined system (i.e. two constraints and two unknowns), and the accuracy is nearly as good as with complete Doppler coverage. However, with three or more periapses, the filter still only has two constraints, and will converge to an arbitrary pattern that meets the constraints. A sample case with complete Doppler data available, but with 5 periapses worth of data artificially removed, was run with and without accelerometer data to demonstrate this effect. Two cases with Doppler and accelerometer data were run. One with only the accelerometer derived ΔV vector, and one with the ΔV vector plus the time centroid. Fig. 6 shows the formal filter uncertainties for this case. Note how the down-track uncertainties grow to 10 km with only Doppler, but are maintained to less than 1 km with the accelerometer data. Figure 7 shows the estimated scale factors with and without accelerometer data. Note the arbitrary linear pattern of the estimated scale factors for the Doppler-only case compared with the much better determined variability with accelerometer data.

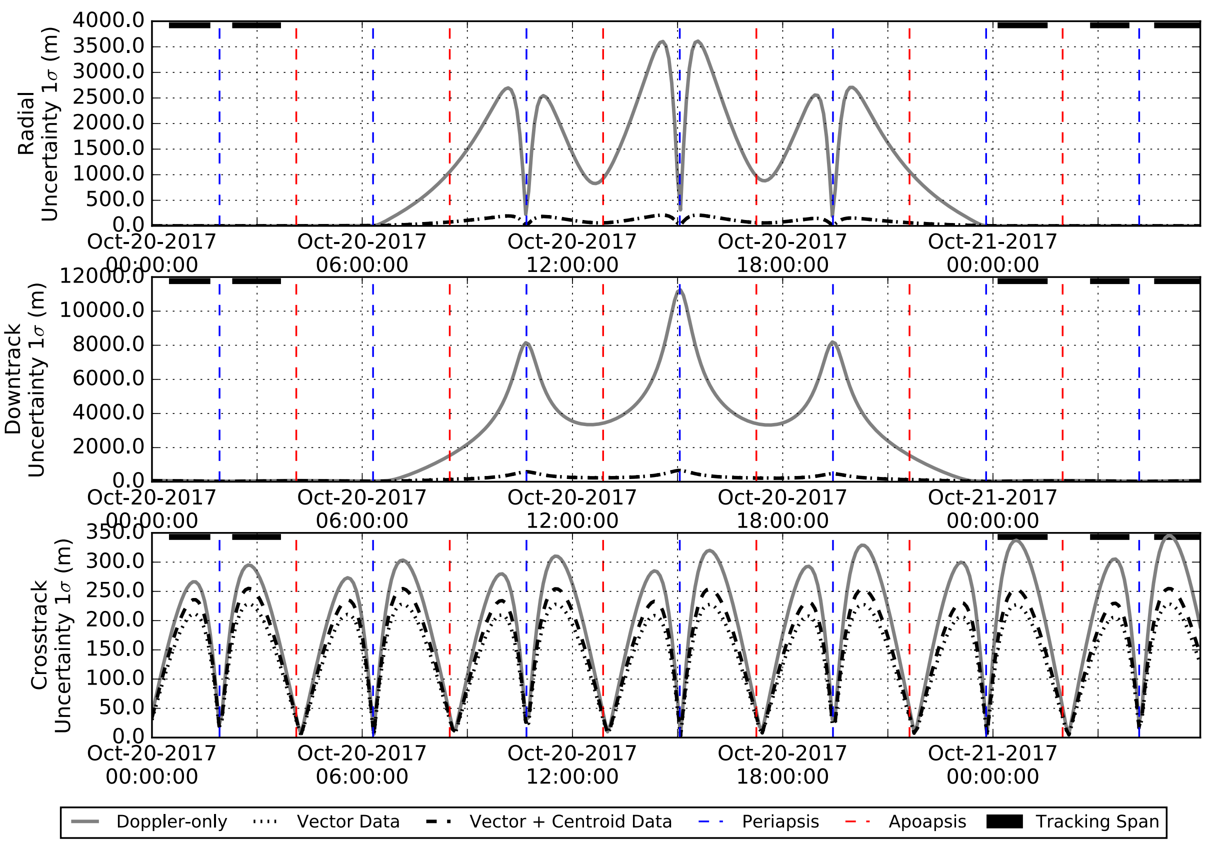

Fig. 6: Filter uncertainties with and without accelerometer data.

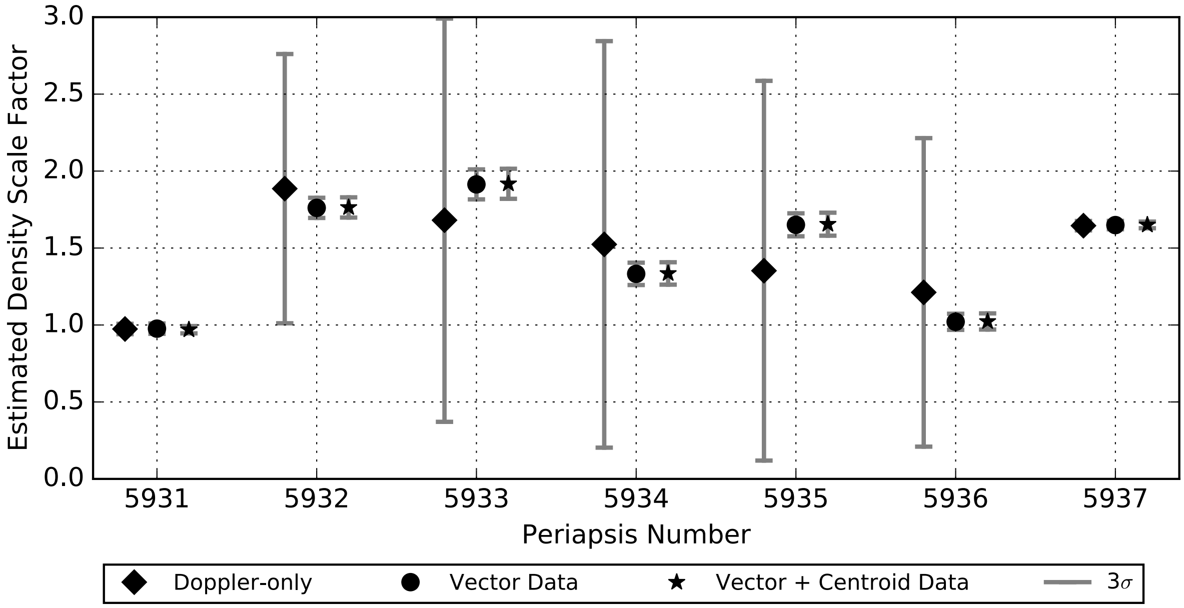

Fig. 7: Estimated scale factors with and without accelerometer data.

VII. Density Behavior

Although constraints prohibited any flexibility in the choice of time, the MAVEN aerobraking actually occurred during a near optimal period: between Ls 339.5 – 5.6 degrees. This is outside of the typical major dust storm season, so the atmosphere was expected to be relatively quiet. The density at periapsis was not expected to change quickly – requiring frequent ABMs – until mid-April.

Without getting into detailed science, in addition to the seasons on Mars, the density behavior depends on several parameters. One can examine the Mars-GRAM predicted density at a constant altitude, along with the periapsis altitude trend and the latitude. Due to MAVEN's orbit and the oblateness of Mars (specifically J3), its periapsis altitude will vary by approximately 55 km as the periapsis latitude varies between ±74 degrees. The minimum altitude occurs when periapsis approaches the south pole, and remains there for a four-month extended period of time due to the flattening of Mars at the poles. (In terms of the aerobraking trajectory, the periapsis altitude levels off around March 25, near -40 degrees latitude. Then it remains relatively constant for four months, or the remainder of aerobraking.) The spacecraft will also be near or in the polar vortex around that time, which could further complicate the density behavior. So, if the density remained constant at a constant altitude, one would expect the density observed by MAVEN to increase as its periapsis latitude trends south. The predicted density profile at a constant altitude during aerobraking is shown in Fig. 8. Note that the density does not vary greatly until early April.

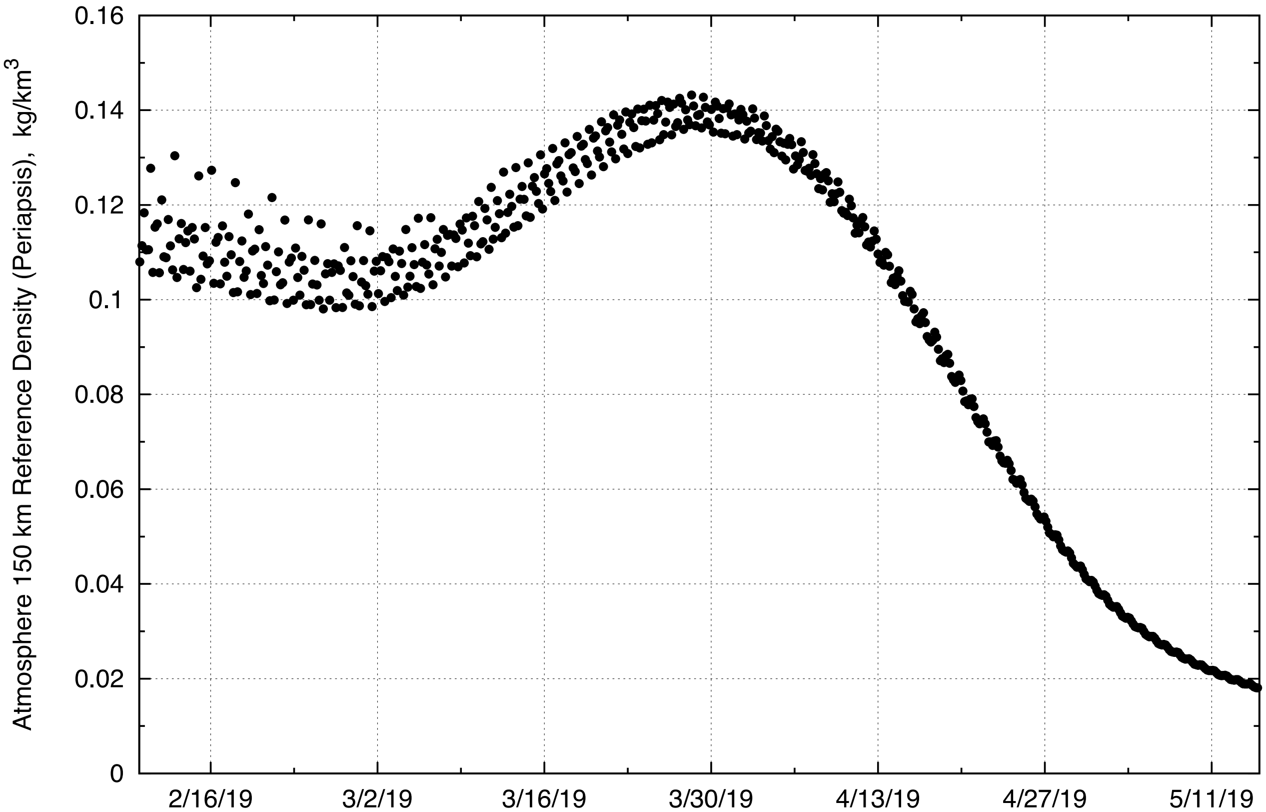

Fig. 8: Mars-GRAM predicted atmosphere behavior at a constant (150 km) altitude.

Looking at Figs. 8 and 9, the naturally decreasing periapsis altitude in the first half of aerobraking would result in periodic ABMs, with a period of minimal or no ABM's in March where the increasing density trend (at a constant altitude) balances out the decreasing altitude. However, by early April, the periapsis altitude will have flattened out while the density (at a constant altitude) is predicted to be decreasing sharply. So, one would expect frequent ABMs to be required during that period to keep MAVEN in the corridor and at acceptable densities to finish aerobraking. Fig. 9 shows an example of a predicted aerobraking strategy that was generated in late 2018. This trajectory flew at lower densities in order to end in early May, a little before the hard deadline for ending aerobraking. If one looks closely, one can see where the ABMs occurred in this example by the discrete jumps in the periapsis altitude.

It turned out that the actual density behavior was not consistent with Mars-GRAM. Fortunately, it behaved such that the density would have stayed at the desired place in the corridor throughout aerobraking with no corridor control ABMs. (See Fig. 4.) This was significantly helped by being able to end aerobraking early, thereby avoiding the period in April and May where frequent ABMs were expected.

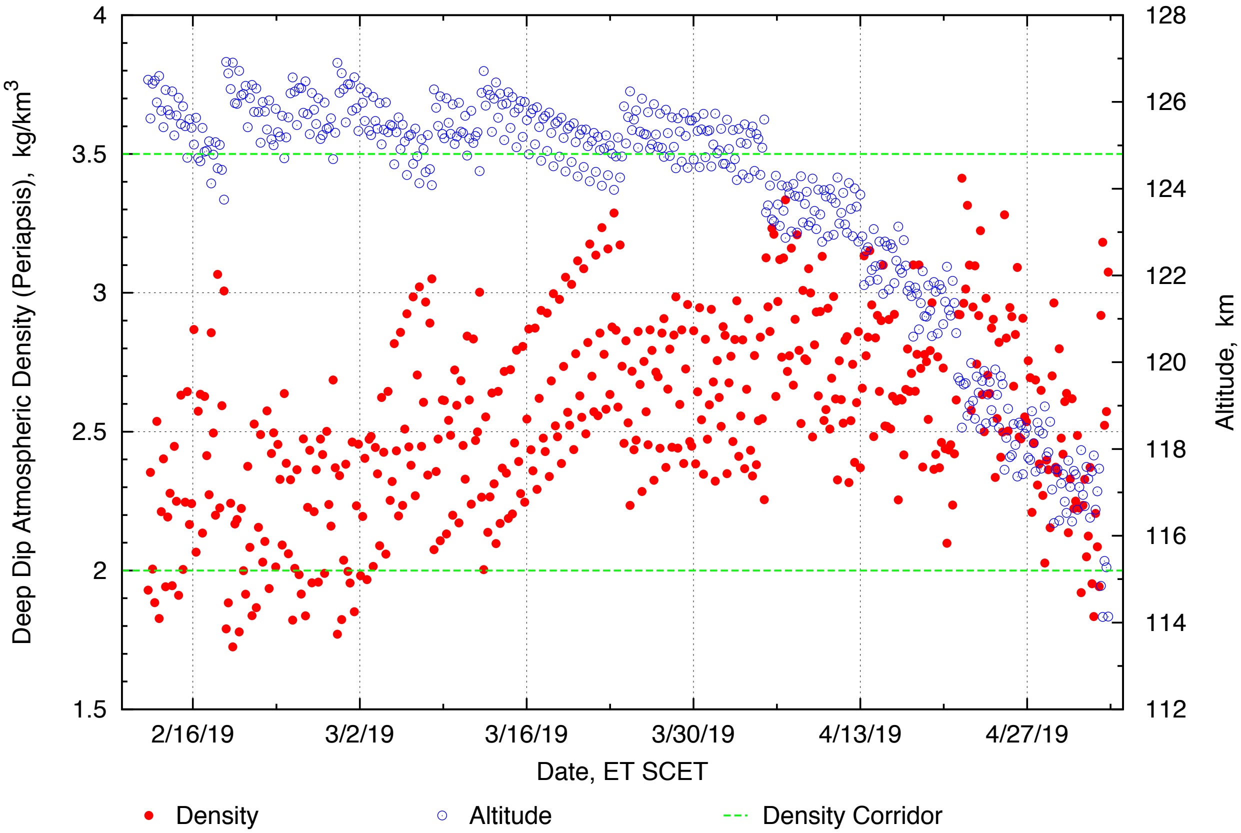

Fig. 9: Periapsis density and altitude during aerobraking.

Since Mars-GRAM was used as the atmosphere model, Navigation used a factor to scale the Mars-GRAM density to the actual value it observed. A plot of the density scale factors (DSF) that Navigation estimated during aerobraking is shown in Fig. 10. The green points are the DSFs Navigation estimated on each orbit. The blue line is the DSF assumed in the trajectory prediction model. The red points are the periapsis altitudes. This plot shows that, after jumping to densities which were much larger than predicted with the maneuver into aerobraking, the densities gradually "dropped down" close to the values predicted by Mars-GRAM. In the latter part of aerobraking, the density followed the Mars-GRAM model fairly consistently (though biased ~20-30% larger than Mars-GRAM). One can also observe the difficulty of trying to determine an accurate density factor to use in the predicted trajectory propagations. For example, by 20 February Navigation had consistently seen higher density scale factors for several days. So, the factor used in the prediction was increased in the delivery that day. However, as soon as that was done, the estimated density scale factors dropped again, resulting in a "degraded" prediction. (It was still well within the expected accuracies, though.)

Figure 10 also supports the previous discussion of the observed density scale heights during aerobraking. Before the aerobraking walk-in with ABM-1A, the density scale factor was 1.3-1.5. However, immediately after the ABM the factor suddenly increased to 2.6. Mars-GRAM had predicted an effective density scale height for this maneuver of 8.3 km. What was actually observed was approximately 6.5 km. In other words, the density was nearly twice as large at the aerobraking altitudes than expected from Mars-GRAM. On the other hand, during walk-out the density scale factor remained approximately the same, implying the density scale heights were similar to the Mars-GRAM model.

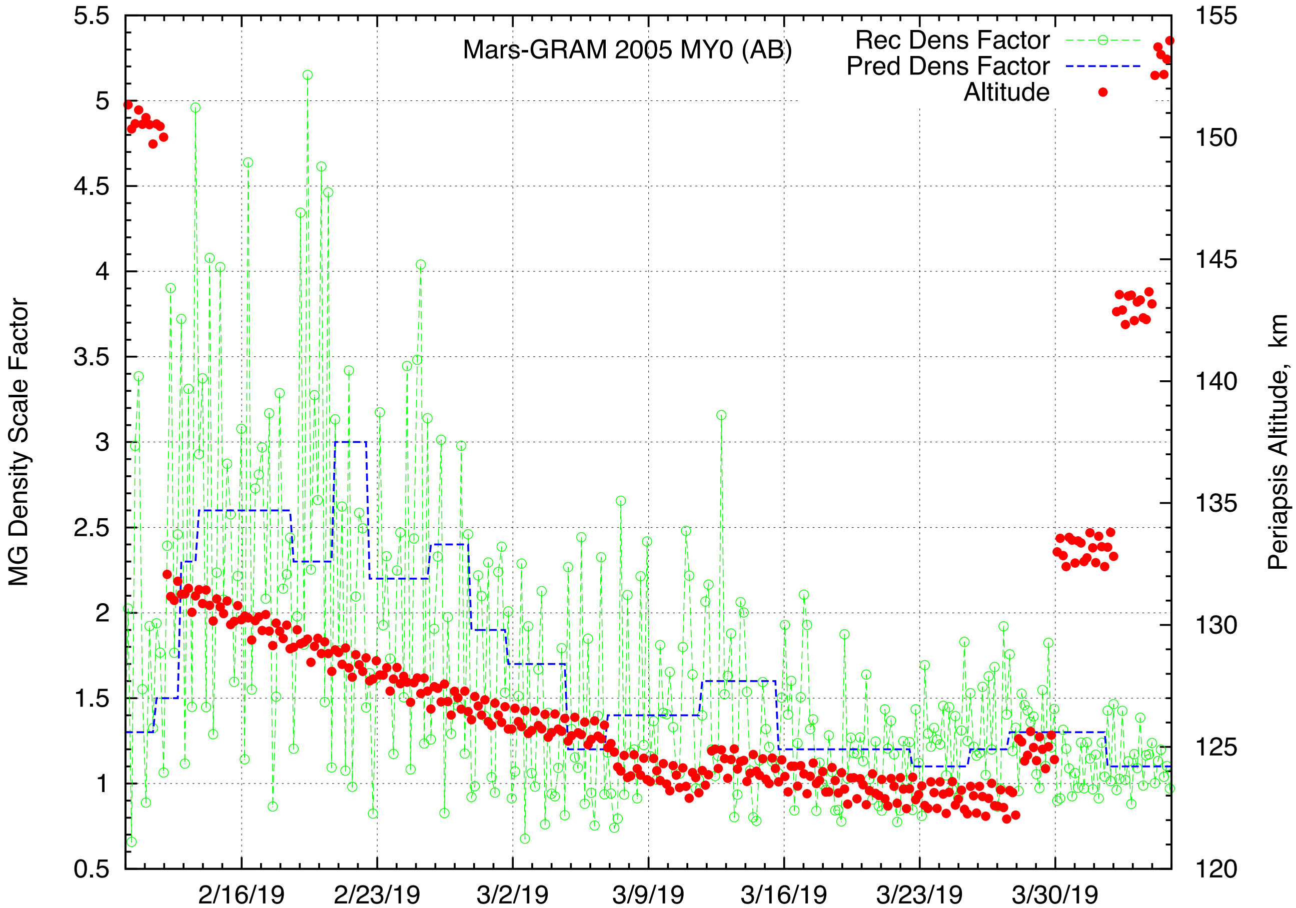

Fig. 10: Navigation scale factor on the Mars-GRAM Map Year 0 density model.

Figure 11 displays the information in Fig. 10 in a different format. The DSF is "normalized" to the DSF used in the prediction (calculated as (Predict_DSF – Reconstruct_DSF) / Predict_DSF). Thus, it displays the orbit-to-orbit variation of the DSF around a "mean" value (the predicted DSF). Figure 11 shows that the predicted density bias offset was well within the assumed 3-sigma 40% error, although at the beginning of aerobraking the orbit-to-orbit density variability was above the 3-sigma 105% assumption. (A comparable plot over the entire MAVEN mapping mission gives similar results.) This validates the assumptions used in the Navigation covariance analyses. Note that the variation in densities can be larger than the aerobraking density corridor (Fig. 4). The density variability, though, decreased significantly as aerobraking progressed.

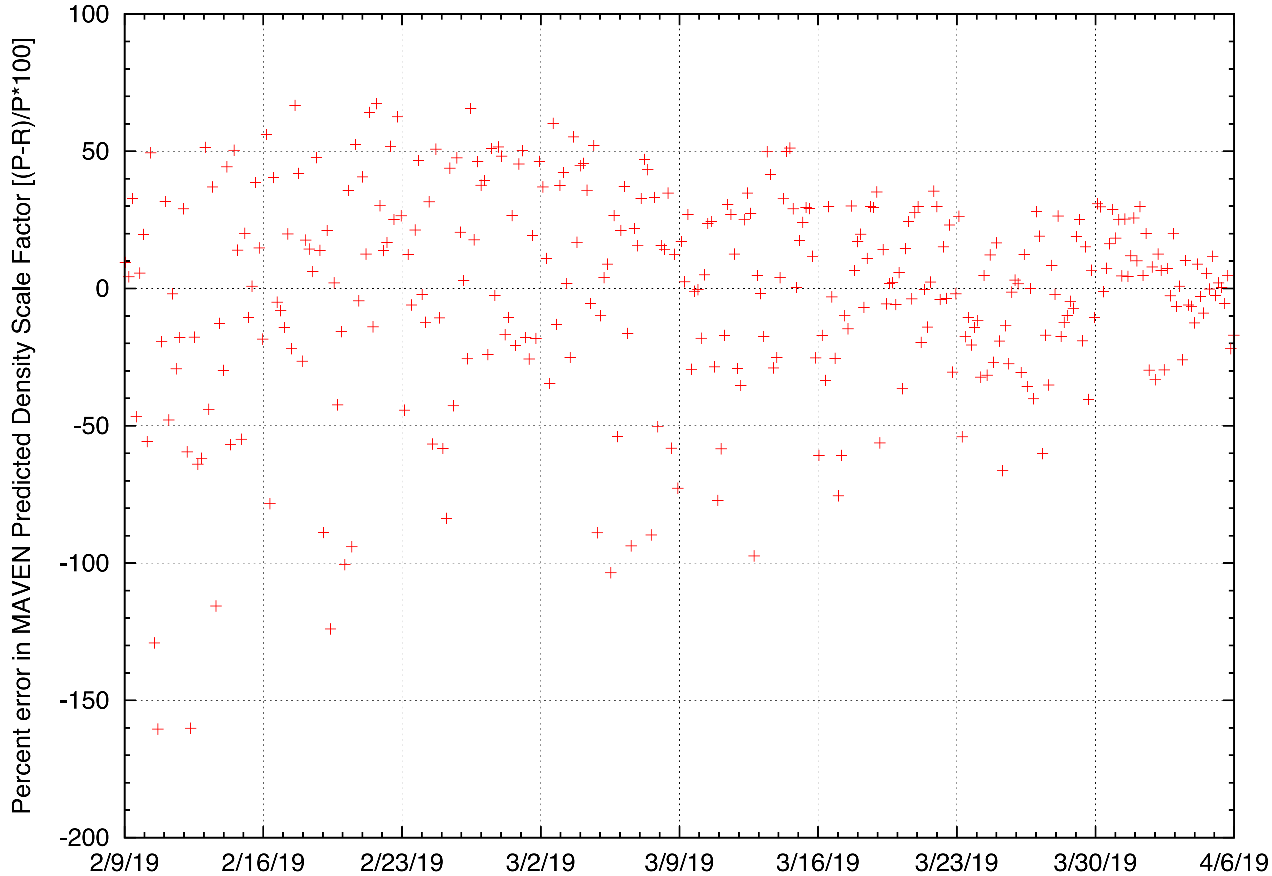

Fig. 11: Orbit-to-orbit variation in the density scale factor, referenced to the predicted scale factor.

In the aerobraking phases of previous missions, a sinusoidal wave-like pattern in the densities versus Mars longitude could sometimes be observed. These wave signatures might not last long, and could change due to the progression of time and/or the spacecraft traveling in a different geometry or area of the planet. However, in the case of MRO, there were a few times that this wave pattern was able to be added to the prediction DSF model, enhancing the Navigation prediction accuracy. For MAVEN, this was never done. The predictions were adequate, and there was never enough confidence that an accurate enough wave pattern could be derived for the prediction model which would be valid long enough to improve rather than degrade the prediction accuracy. As two examples, Fig. 12 shows a plot of the DSF versus longitude near the beginning of aerobraking. A 2-cycle density or DSF wave is noticeable with peaks around 130 and 270 degrees longitude. Figure 13 shows a similar plot towards the end of aerobraking. In this case there was only a 1-wave signature, and it was less pronounced. By the end of aerobraking there was no discernable wave property. The Atmosphere Advisory Group is working on a paper which will give a detailed analysis of these wave features [17].

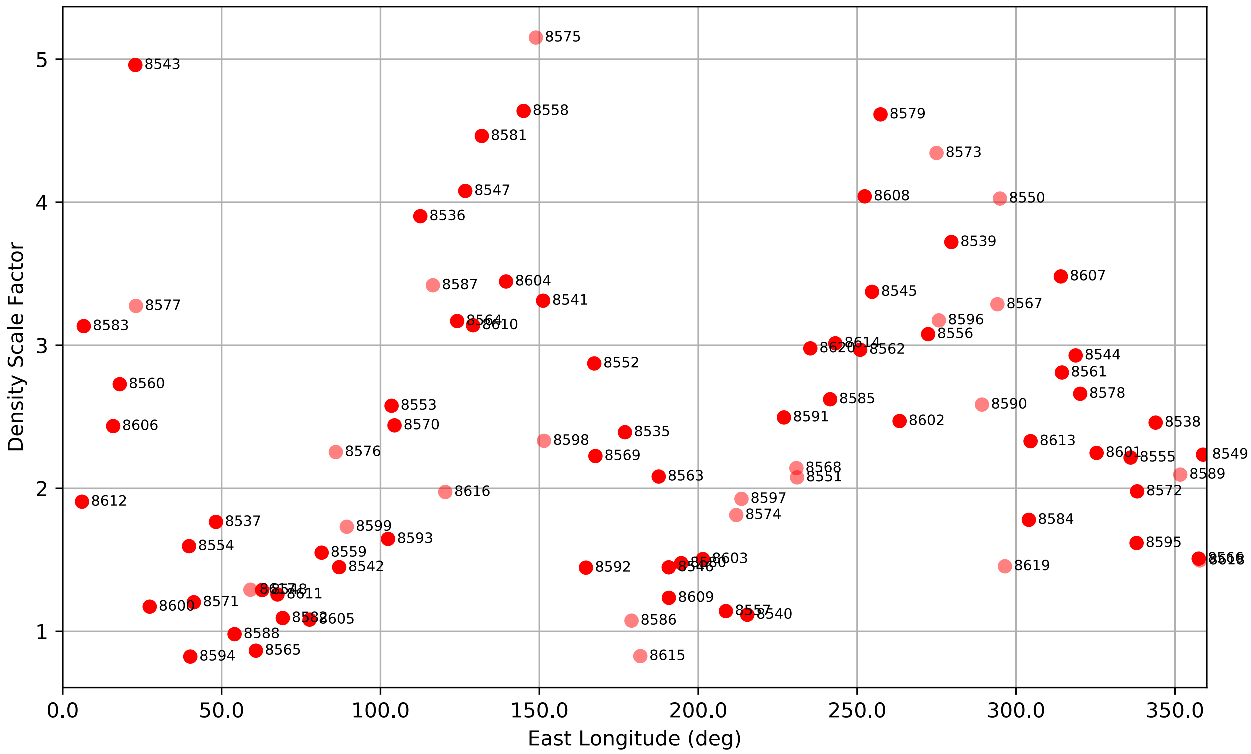

Fig. 12: Variation in longitude of the density scale factor on Mars-GRAM (Orbits 8535-8620).

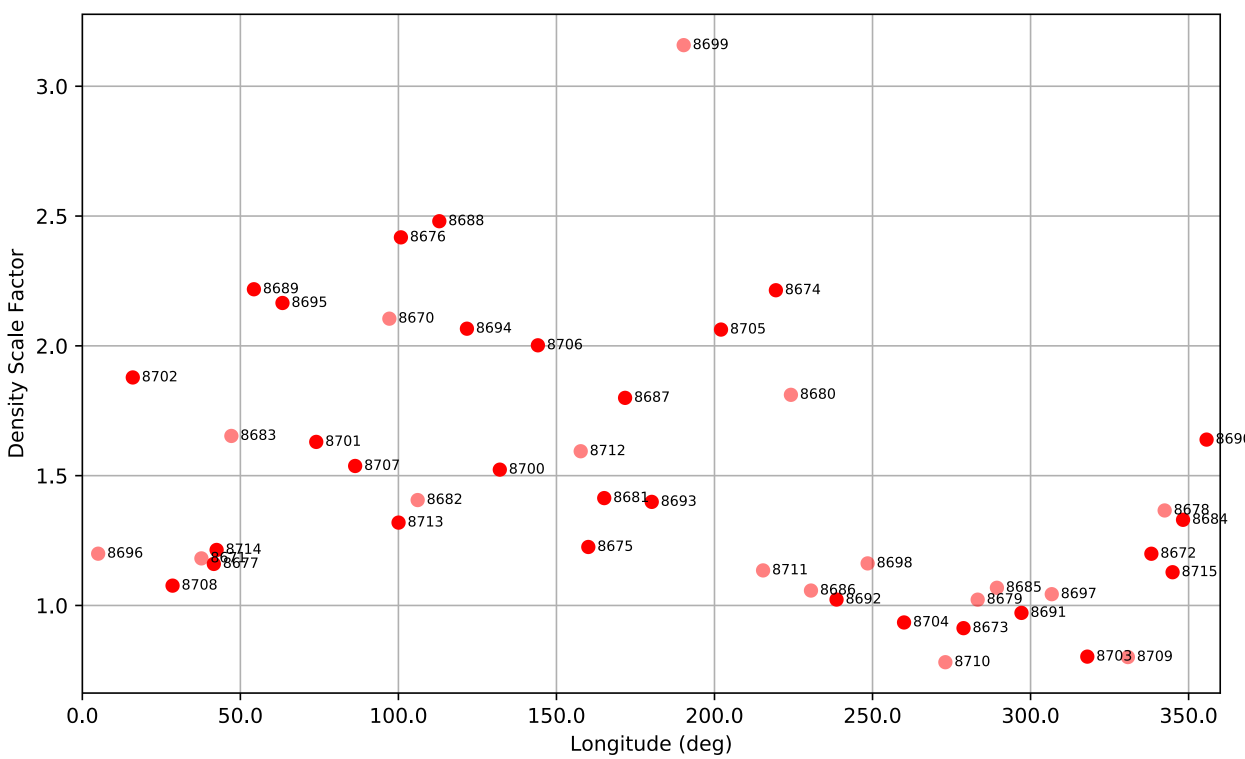

Fig. 13: Variation in longitude of the density scale factor on Mars-GRAM (Orbits 8670-8715).

VIII. Collision Avoidance

Since MAVEN was the spacecraft around Mars with the largest uncertainty in its predicted position, can quickly perform maneuvers, and has frequent planned maneuver opportunities, MAVEN nominally performed the maneuvers to avoid a potential collision with another body around Mars. This "collision avoidance" or "conjunction analysis" is referred to as COLA. Since MAVEN was at much larger densities during aerobraking, the MAVEN prediction accuracies were dramatically worse, resulting in potentially more COLA conflicts. On the other hand, MAVEN could perform maneuvers more frequently during aerobraking.

The distances between the orbits of MAVEN and another body were examined at the point where the orbits cross each other, since such locations were the only place where a collision between the two bodies could occur. If the distance between the two orbits at such a point was small enough, there was a potential for a collision. The difference between the times when the two objects got to that orbit intersection was then examined to determine if there was an actual concern. Since the orbit shape and orientation were relatively well known, the orbit crossings determined "COLA seasons" of potential collision opportunities. Comparatively, the location of a spacecraft within its orbit (e.g. its down-track position or true anomaly) was poorly known. It could be tracked as the COLA season approached, during which time the down-track prediction accuracy of the spacecraft would greatly improve. Figure 14 shows the expected COLA seasons that were determined before aerobraking started.

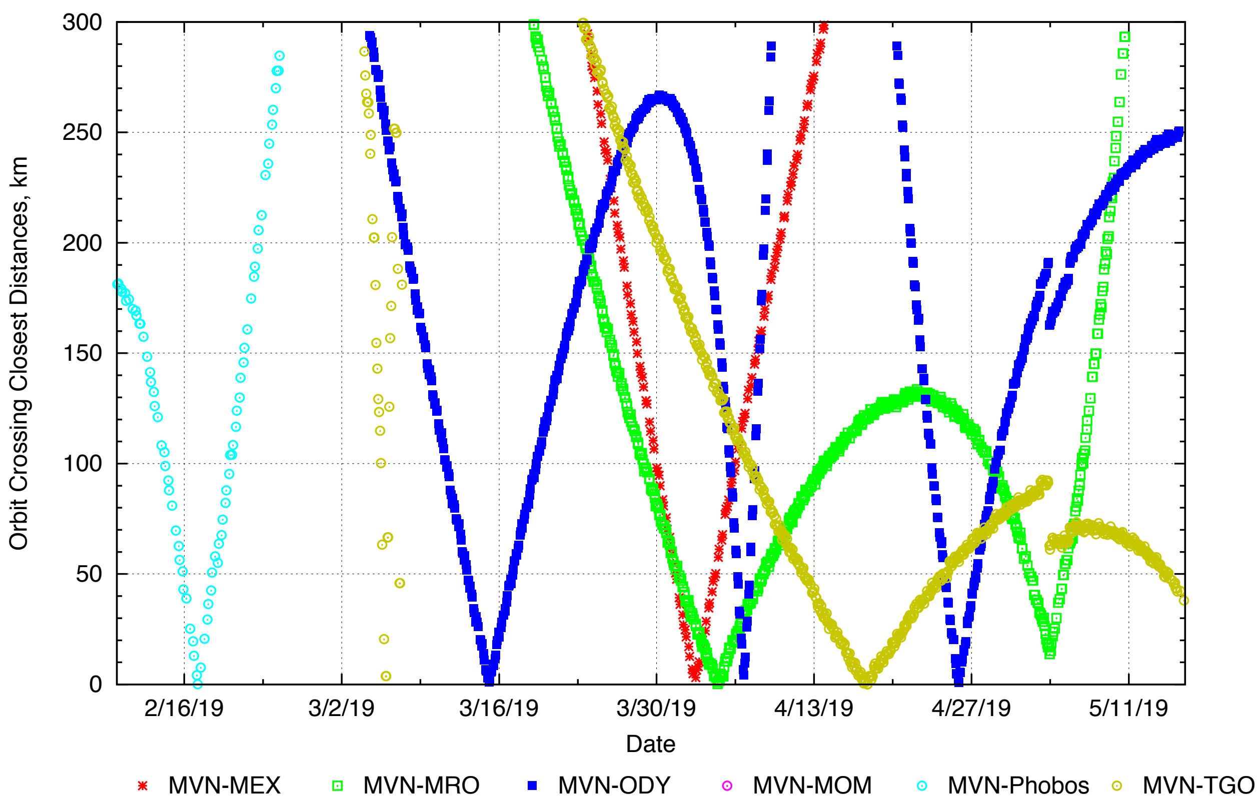

Fig. 14: Predicted COLA seasons around aerobraking.

The Mission Design and Navigation (MDNAV) section at the Jet Propulsion Laboratory (JPL) had an automated process, called MADCAP,* to determine potential COLA concerns as described above [18-20]. The process was run once a day, and accessed the latest predicted trajectories for the bodies orbiting Mars. A summary of the results was sent out via e-mail, and identified "red events" of potential collision concerns. MAVEN Navigation supplied "red

* Multimission Automated Deepspace Conjunction Assessment Process

event" error polynomials for the prediction accuracy of its Orbit Crossing Distance (OXD) and Orbit Crossing Time (OXT).*

For each predicted trajectory delivery, Navigation would examine the current density trend, the expected density in the near future, the potential need for an ABM to keep MAVEN within the corridor, and the potential need for an ABM to avoid any COLA concerns in the near future. A quick meeting would be held with the project, and the ABM decision (if any) would be incorporated into the predict delivery with the ABM that would be executed later that day. (This is the same process MRO followed [11].) The MADCAP process was a good method of notifying people of potential COLA events in the future. However, MADCAP started determining red events fourteen days before a potential COLA event. MAVEN would not execute an ABM to avoid a red event until a few days beforehand. With the large Navigation prediction errors during aerobraking, this often led to many red events. However, as those events approached, they would typically disappear due to the more accurate prediction knowledge. Furthermore, at critical COLA ABM decision times, MAVEN Navigation would perform more accurate COLA analyses, taking into account the actual densities that MAVEN was flying at.

Figure 14 shows that there was a Phobos COLA season near the start of aerobraking. Unlike the near point mass spacecrafts, the significant size of Phobos (~27 km maximum diameter) complicated COLA analyses and increased collision probabilities. This also had the effect of extending the Phobos COLA season over multiple days. Furthermore, the walk-in maneuver could shift this COLA season by a few days. As a result, although MAVEN could not get continuous DSN coverage over the entire aerobraking period, the project did receive continuous coverage over the first week, and near continuous coverage over the second week. That gave MAVEN the capability to perform daily ABMs in order to walk-in to the aerobraking corridor quickly and then maneuver to avoid Phobos, if necessary. After the first maneuver, ABM-1A, MAVEN was already in the corridor, and the Phobos COLA season was narrowed down to 15-16 February (UTC). Fortunately, the post-ABM predicted MAVEN timings relative to Phobos resulted in minimal COLA concerns. Thus, no ABMs were required to avoid Phobos.

The next period of significant COLA concern was near the walk-out. Since MAVEN had made good progress in its aerobraking, it was going to walk-out at the beginning of April. Figure 14 shows that there were three COLA seasons close to each other around that time: MEX, MRO and ODY. Also, with updated TGO trajectories and MAVEN's aerobraking propagation, the TGO COLA season shifted earlier to 10-12 April (depending on the walk-out strategy). COLA analyses with respect to ABMs began in earnest on Wednesday, 27 March, while making a decision on ABM-7B. There was the additional complication that the size of ABM-7B could shift the MRO COLA season before or after ABM-8A. The MEX COLA season turned out to not be a problem, as is typically the case due to its large orbit size. Since MAVEN was near the high-density limit of the corridor, a +0.4 m/s ABM-7B was executed to ensure that the density stayed within the corridor (Fig. 4). It also reduced the densities for better down-track prediction accuracies for the future COLA analyses, reduced the ΔV which would be needed for the walk-out, and gave some preliminary information on the current density scale height.

The main purpose of ABM-7C was to start the walk-out to the desired apoapsis altitude target (4560 km), although the MRO and TGO COLA seasons also had to be investigated – in addition to ensuring that MAVEN was not accidentally maneuvered back into a COLA situation with MEX a day after the ABM. It was decided to perform a +1.5 m/s ABM-7C, which was predicted to move MAVEN to a density of 1.3 kg/km^3. (The actual post-ABM density was 1.0 kg/km^3.) This choice was reasonably good from a COLA perspective, plus there was still time to execute ABM-8A to avoid an MRO or TGO COLA situation.

ABM-8A would bring MAVEN most of the rest of the way to the nominal density corridor, with ABM-8B being used to bring MAVEN into the corridor if it was not already there. It was decided to perform a +1.8 m/s ABM-8A, which was predicted to move MAVEN to a density of 0.32 kg/km^3. It was verified that this maneuver caused no MRO or ODY COLA problems. There was a potential TGO COLA situation on 11 April, nine days later, but there were several maneuver opportunities before then. A +1.8 m/s ABM-8B was executed on 4 April to target MAVEN to 0.11 kg/km^3, near the middle of the nominal density corridor. It was verified that this choice had no ODY COLA problems. It did shift the TGO COLA season to 13 April, but appeared unlikely to have any TGO COLA difficulties. The potential maneuvers ABM-8C and OTM-229 also occurred before 13 April, allowing for the avoidance of a TGO COLA event in the unlikely event that it was of concern after ABM-8B.

The other two COLA seasons in March (TGO and ODY) were significantly less stressing, and were analyzed at the ABM meeting(s) preceding their execution. The actual close approaches of MAVEN with other objects during

* For MAVEN aerobraking: $OXT(t) = 15 + 150*t + 0*t^2$ [sec]; $OXD(t) = 0.7 + 0.9966*t + 0.0126*t^2$ [km]; t = days of prediction to the COLA event. The polynomials had some conservatism since they assumed that MAVEN was near the high-density corridor limit (5.5 kg/km^3).

aerobraking is shown in Fig. 15. There were two close approaches around 20 km: TGO on March 5 and MRO on March 30. The closest approach to Phobos was 181 km (from the center of Phobos), and occurred on 18 February.

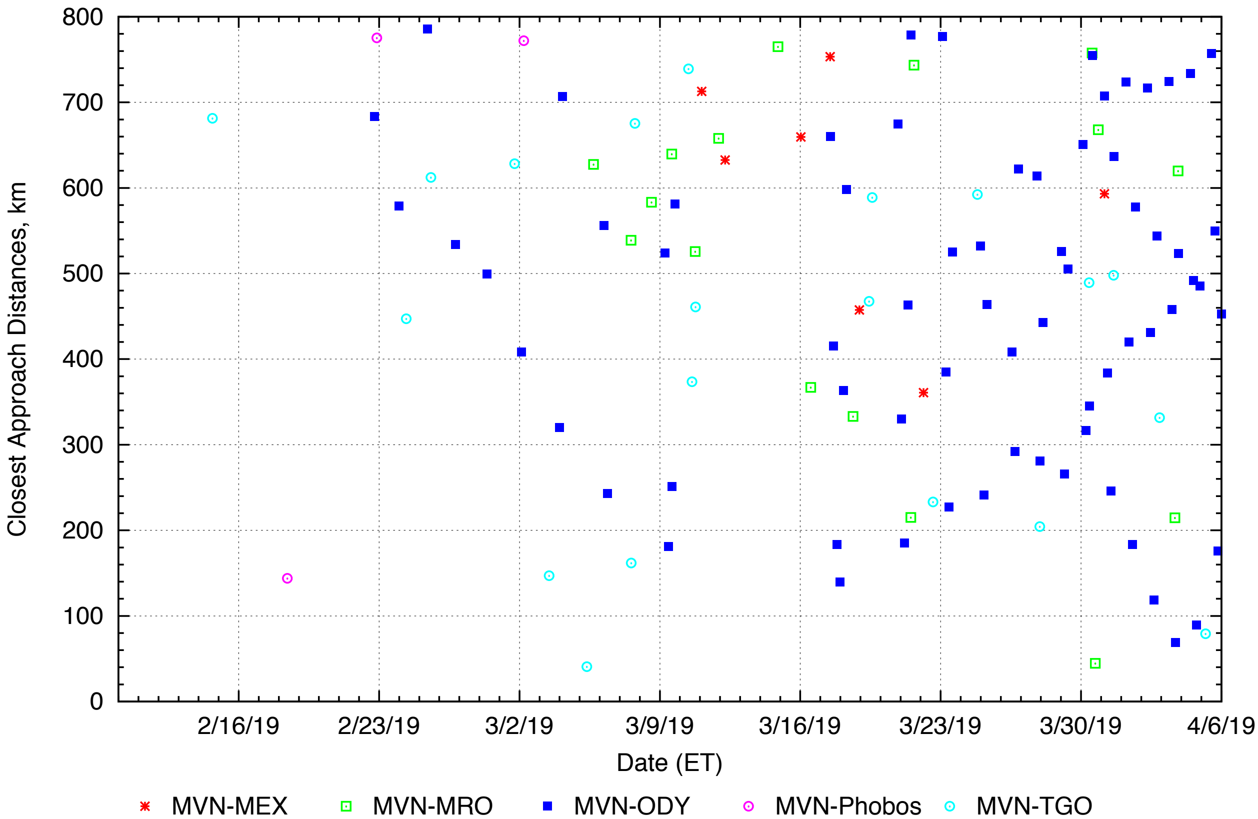

Fig. 15: Actual closest approaches between MAVEN and other satellites.

IX. Summary and Conclusions

Although not designed for aerobraking, MAVEN was able to perform a light aerobraking in order to accomplish two main objectives: decrease its orbit size to better support lander relay operations; synchronize its orbit for support of the M2020 EDL. Unlike the aerobraking phases of previous missions, Navigation was able to support quality science by continuing to meet the nominal science accuracy requirements. The inability to get continuous DSN coverage for aerobraking was resolved by adding accelerometer derived data to the Navigation orbit determination filter analyses. With the current over-subscription of the DSN, this may be required for any future aerobraking which relies solely on DSN tracking and 2-way radiometric data.

X. Acknowledgements

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