MAVEN Orbital Trajectory Analysis: Design and Implementation of Lander Relay Support

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NASA's successful Mars Atmosphere and Volatile Evolution Mission (MAVEN), currently engaged in a survey of the Martian atmosphere and its evolution over time, has successfully completed a series of orbit changes, including a two-month aerobraking campaign, to satisfy additional mission roles. Launched on 18 November 2013, it entered Martian orbit on 22 September 2014. Having finished its primary one-year mission, the NASA Mars Program Office (MPO) started discussions with the MAVEN project on feasible options for extending the mission lifetime along with providing support for various Mars lander functions. MAVEN is the latest of the three active NASA Mars orbiters, with no others planned for the foreseeable future. Given that the landers need orbital relay support for years to come, and the MRO and Odyssey orbiters are aging, MAVEN's role in providing critical orbital relay support has become increasingly important. After several years of studies, MPO directed the MAVEN project in 2018 to reduce its orbit size to provide better telecommunications relay support for Martian surface landers and to support Mars 2020 EDL under the constraint that MAVEN will have enough fuel to operate until 2030. As a part of this effort, the recent aerobraking campaign was one of several steps crucial to accomplishing this goal. This paper discusses the challenges of the entire mission design and its distillation into a concrete set of targeted objectives. With the successful orbit change, MAVEN will be able to provide support for the Mars 2020 relay activities from EDL through surface operations beyond 2030. This effort can serve as an excellent example for future missions having similar needs and requirements.

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I. Nomenclature

e	=	Eccentricity
dt	=	Time step
$Gm♂$	=	Standard Gravitational Parameter for Mars (♂), also known as $\mu♂$
h	=	Height
i	=	Orbital inclination (Mars' equator)
J_2	=	Second degree spherical zonal harmonic coefficient
J_3	=	Third degree spherical zonal harmonic coefficient
n	=	Mean motion
p	=	Semi-latus rectum
ρ	=	Density (expressed as kg/km^3)
r	=	Radius
r_{eq}	=	Equatorial radius
t	=	Time
f	=	True anomaly, referenced to pericenter
v_{orbit}	=	Orbital velocity (speed)
ω	=	Argument of periapsis
Ω	=	Longitude of the ascending node

II. Introduction

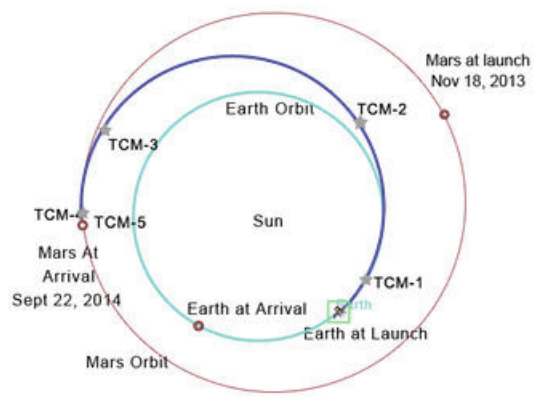

Fig. 1 MAVEN Spacecraft Launch to Transfer Orbit to Mars

The Mars Atmosphere and Volatile Evolution Mission (MAVEN) is a Mars Scout Program initiative mission designed to conduct a survey of the Martian upper atmosphere, focused on the interactions between the atmosphere and the sun and the solar wind, and the Martian atmosphere's evolution over time. Evidence suggests that much of the Martian atmosphere has been lost over billions of years, and this mission is focused on the loss of water and other crucial volatiles in the atmosphere to space [1]. Launched on 18 November 2013, the MAVEN spacecraft arrived at Mars ten months later on 22 September 2014 (Fig. 1). MAVEN started its primary science phase on 16 November 2014 in a Nominal Science Orbit (NSO) with an orbital period of 4.5 hours, an apoapsis altitude of 6200 km and a periapsis altitude of approximately 150 km. MAVEN conducted more than 7000 atmospheric passes in this orbit, plus nine targeted "Deep Dips" of approximately 10 days duration, for atmospheric observations at lower altitudes [2].

No orbiters are planned for the foreseeable future, and there were concerns about the aging current orbiter relay assets, Mars Odyssey (ODY) and Mars Reconnaissance Orbiter (MRO), for the planned additional landers that would need orbital relay support. As a result, after the end of MAVEN's primary science phase, the NASA Mars Program Office (MPO) started discussion with MAVEN and the surface landers (represented by the Mars 2020 project) to incorporate MAVEN into a long-term plan of relay assets around Mars. This required MAVEN to eventually increase its periapsis altitude to reduce atmospheric perturbations on the orbit. This higher orbit would significantly increase MAVEN's trajectory prediction accuracy, and greatly extent its End of Mission (EOM) timeline by extending the useable propellant on the spacecraft.

This paper summarizes the Navigation effort to support MPO in the development of future requirements for MAVEN. A feasible strategy was agreed upon where MAVEN would aerobrake to lower its apoapsis altitude to ~4500 km, raise the periapsis altitude to ~180 km minimum altitude, support Mars 2020 EDL, and still have sufficient propellant to last past 2030.

III. The Current Nominal MAVEN Orbit

For the primary science mission, the Nominal Science Orbit provided support for the MAVEN mission's scientific research with an elliptical orbit that had an orbit period of ~4.5 hours (~6200 km apoapsis altitude) and an average periapsis altitude of 150 km. Periapsis, designed nominally to keep the spacecraft in an atmospheric corridor with a mean atmospheric density (ρ) of 0.05–0.15 kg/km^3, varied by tens of kilometers (130-180 km altitude). Periapsis rotated around Mars over time due to nodal progression, allowing the examination of different regions, seasons and local solar times. The spacecraft was maintained in the mean atmospheric density corridor by Orbit Trim Maneuvers (OTM). As these densities were large enough to degrade the orbit over time, a Period Correction Maneuver (PCM) had to be executed occasionally to return the orbit period to near 4.5 hours (and ~6200 km apoapsis altitude). Angular momentum desaturations were regularly required (initially every orbit) to dump the accumulated momentum from the spacecraft reaction wheels. Periodically a Deep Dip was executed to acquire science in a lower region of the atmosphere. The Deep Dip required lowering the periapsis to a corridor with a mean density of 2.0–3.5 kg/km^3. The process of walking into the Deep Dip corridor, taking science and walking back to the nominal science density corridor took approximately 10 days and a significant amount of propellant. The degradation of the MAVEN orbit due to a Deep Dip was equivalent to half a year or more in the nominal science corridor. This had the secondary effect of requiring more frequent PCMs. Figure 2 shows a plot of the orbit period from the start of the primary science phase. It shows the nine Deep Dips (DD), along with the four PCMs required to reset the orbit period, and the effect of the Aerobraking (AB) phase.

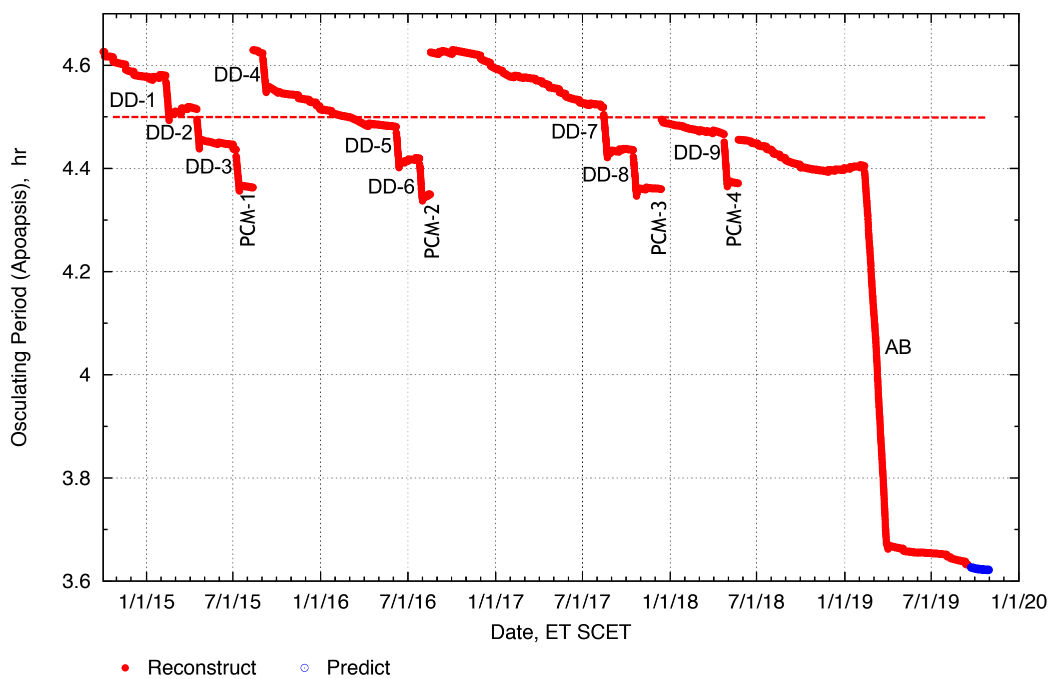

Fig. 2 MAVEN Orbit Period Over Time

The nominal orbit was designed to support the science objectives of MAVEN, but uses significant propellant over time. In order to significantly extend MAVEN's lifetime, its periapsis altitude could be increased to minimize atmospheric drag on the spacecraft, allowing density corridor control to be stopped and reducing the angular momentum desaturations. This is termed the Science Relay Orbit (SRO). However, the increase in periapsis altitude would dramatically decrease the atmospheric science of MAVEN. As a result of the efforts described in this paper, the relay support for Mars landers was to become MAVEN's primary purpose. The loss of science was acceptable to MPO, relative to the gain in mission lifetime.

IV. Development of MAVEN Orbital Trajectory Goals

The high-level considerations of these changes to the MAVEN orbital trajectory were evaluated on a continuum between optimal science returns and optimum relay support. The key was to avoid choices that did not provide optimized returns – i.e. that resulted in cases where science and relay support was worse. Significantly, neither the MAVEN spacecraft, since it did not have a movable high gain antenna or movable solar panels (Fig. 3), nor its elliptical orbit, was optimal for surface relay support. A series of studies conducted in 2016 and 2017 helped clarify the trade space considerations for the numerous options to transition MAVEN to a primary relay satellite, and a clear methodology was used to compare the various trade choices.

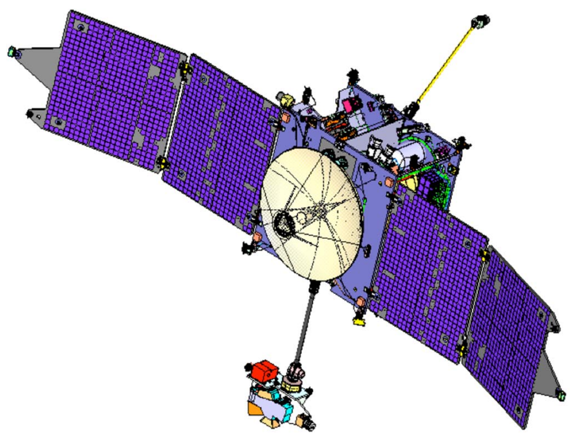

Fig. 3 MAVEN Spacecraft – Showing High-Gain Antenna (HGA) and Solar Panel Configuration

A. 2016 Studies

1. Initial MPO Study Task for MAVEN

In 2015 after the primary science mission finished, MPO requested that MAVEN perform a set of studies to support decisions on the future of MAVEN [3]:

1. Operate MAVEN as a relay orbiter through at least 2025.
2. Provide critical communication service to the Mars 2020 spacecraft during Entry-Descent-Landing (EDL)
3. Maintain an option to reduce MAVEN's apoapsis to ~1000 km to increase MAVEN's relay performance for the Mars 2020 surface mission.

Additionally, sufficient propellant would have to remain at the End Of Mission (EOM), to place the spacecraft into a 500 km periapsis disposal orbit. This disposal orbit was to provide improved planetary protection and avoid possible collisions with other orbiters. Possible options for extending the mission lifetime out to 2030 were also requested.

2. Initial MAVEN Studies

The nominal MAVEN mission plan was to continue in the NSO, performing a total of 10 Deep Dips, until the spacecraft propellant was depleted. Four Deep Dips had already been completed in the primary science phase. For the MPO study any MAVEN mission objectives could be discarded to meet the MPO requirements, and not all requirements had to be met. This led to a myriad of potential variations. The large trade space of was made more manageable through a couple of methods: a simplification in the method of predicting propellant usage, and a preliminary design tool (Section V) to quickly estimate the trajectory, mission lifetime, and Mars 2020 EDL support. With no future NASA Mars orbiters planned, MAVEN's lifetime was the most important of the MPO requirements. This was tracked in several ΔV studies where the total size of the maneuvers (or ΔV) was considered with other propellant expenditures to determine when the estimated spacecraft propellant would be exhausted. The other propellant expenditures of MAVEN mainly consisted of the regular angular momentum desaturations (unlike many of the other Martian orbiters). To simplify this study, propellant was divided into key categories and each was assigned a constant ΔV. This approach simplified the ΔV budget into a set of independent categories or blocks of propellant, which could be easily manipulated into any desired strategy. The inaccuracy of this approach was unimportant compared to the inaccuracies of the propellant usage estimates and long-term mission lifetime estimates [4]. As an example, Figure 4 shows one such strategy: (1) all ten Deep Dips are executed, (2) no aerobraking, (3) a "small" PCM-3 of 20 m/sec – allowing the orbit period to drift below the project science requirement, and (4) no Mars 2020 support. In this case MAVEN stays in the NSO until 2020 and the spacecraft propellant lasts until 2026.

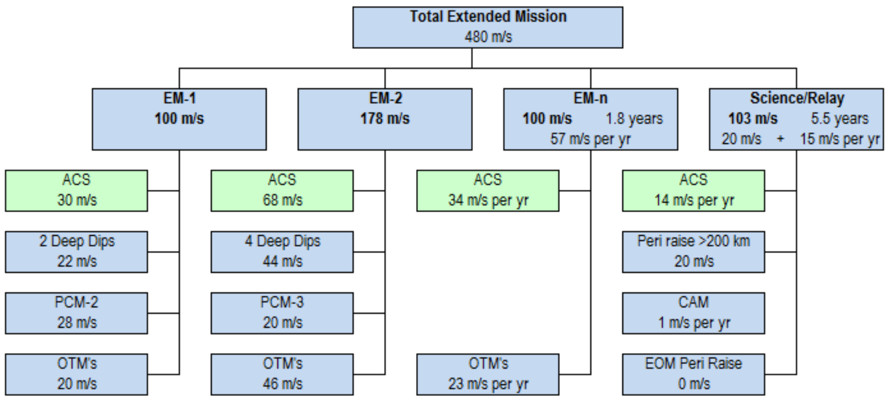

Fig. 4 Modified Baseline ΔV Budget for Extended Mission Relay Study

As time progressed, improvements in the propellant cost estimations due to increases in operations efficiencies were included in these studies. Table 1 shows propellant costs assigned to the major categories of these studies over time:

Table 1 Estimated Propellant Costs by Category

Category (kg per year)	2016	2017	2019
Standard NSO	28.5	19.5	20.5
OTMs	11.5	10	10
Momentum desaturations*	17	9.5	10.5
Single Deep Dip – 4 kg additional for orbit degradation effect	5.5	5.1	N/A
Mars 2020 EDL support	25	21	9.5
SRO	7	5.1	6

As Table 1 shows, in the initial 2016 studies the momentum desaturations were expected to use much more propellant per year than the OTMs. The blue shaded 2017 and 2019 columns show the efforts to reduce these costs with momentum management as discussed below. This table also shows how expensive a Deep Dip was in terms of propellant – one deep dip used nearly as much propellant as an entire year in the SRO. Furthermore, Figure 1 shows that a short duration Deep Dip degrades MAVEN's orbit dramatically. Including a correction for this effect, a Deep Dip used nearly as much propellant as a year of OTMs in the NSO. Thus, the removal of Deep Dips was a simple means to save propellant. A judicious choice of which specific Deep Dips to execute could also significantly decrease the propellant use by adjusting the trajectory to a more favorable position to support the Mars 2020 EDL.

* To simplify the process, all non-OTM propellant usage was included in this category. However propellant usage of the momentum desaturations was the major contributor to this budget.

B. 2017 Studies

1. Revised MPO Study Task for MAVEN

A second iteration of these studies was performed in 2017 for MPO. As a result of the 2016 studies, the 2017 study requests were revised as follows:

1) The 500km periapsis altitude EOM requirement was dropped. The propellant needed for this requirement was equivalent to approximately a decade of SRO operations, making it difficult to find a feasible MAVEN mission scenario extending to an acceptable mission end date.
2) An option of aerobraking down to 4500 km apoapsis altitude was added. Although Maven could not aerobrake, due to the spacecraft configuration, with excessive heating at the densities of the Mars Global Surveyor (MGS) [5], Mars Odyssey (ODY) [6], and Mars Reconnaissance Orbiter (MRO) [7] missions, there was a potential option to aerobrake with minimal concerns. Indeed, it would be possible for a shallow aerobraking campaign to be successful – effectively a succession of Deep Dips. Serious problems were seen in MAVEN trying to aerobrake down to a 1000 km apoapsis altitude in a preliminary study. While it was theoretically possible MAVEN might be able to aerobrake down to 1000 km, due to science and operations concerns the compromise of 4500 km was seen as a much less problematic approach.
3) Increased emphasis was placed on MAVEN lasting until 2030.
4) An additional set of analysis were requested with estimations of the expected benefit of momentum management. The 2016 studies had noted that regular momentum desaturations were a major propellant expense. The spacecraft had a long boom with many science instruments attached (Fig. 3). The orientation of this boom relative to the spacecraft and Mars could greatly affect the torque on the spacecraft which the momentum wheels would have to absorb. The Spacecraft Team had started a very preliminary investigation of changing to "Gravity Gradient Neutral" (GGN) spacecraft bus and boom orientations that would still satisfy science and greatly reduce torque on the spacecraft. By choosing the appropriate GGN orientation for each event sequence, gravity torque would help manage the spacecraft momentum and significantly reduce the desaturations.

The additional year in orbit for MAVEN provided a couple of benefits as well. First, MAVEN had doubled its time in orbit, allowing estimated propellant usage to be refined. Second, a year of possible variations in trajectory designs had passed, including the execution of two Deep Dips, helping to narrow the trade space of possible mission choices.

2. Revised MAVEN Studies

Many analyses were performed in 2017, some of which are shown in Fig. 5 for the case of momentum management. This figure shows a summary of mission lifetime as a function of no aerobraking, aerobraking to 4500 km, aerobraking to 1000 km, Mars 2020 EDL support, maneuvering up to a 500 km periapsis altitude at EOM, and (InSight lander) surface relay support after EDL. These cases were plotted with respect to EOM versus the number of Deep Dips that would be performed after 30 September 2016 – the end of the first Extended Mission (EM-1).

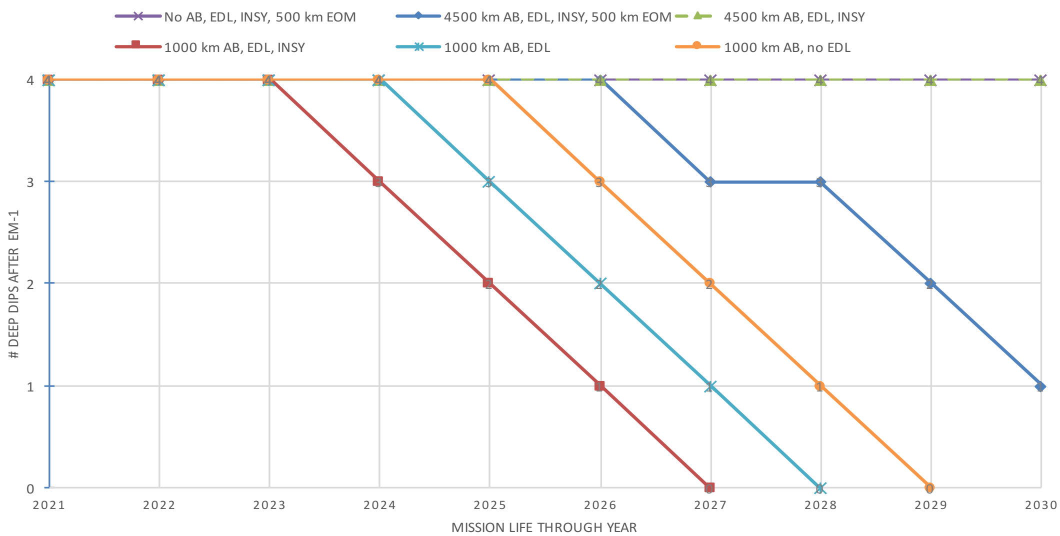

Fig. 5 Mission Duration vs. Mission Options

It was estimated that momentum management might be able to reduce the desaturation propellant usage by 40%. This would have the effect of lowering the desaturation ΔV budget to be equivalent to the OTM budget (Table 1 – blue shaded columns), and increase the EOM by nearly three years. The 1000 km altitude aerobraking scenario was not feasible for MAVEN, neither from a science and mission lifetime perspective, nor from a spacecraft operations standpoint. However, the 4500 km aerobraking scenario appeared feasible, and the GGN momentum management allowed for an extended mission lifetime. Further analyses of specific trajectory and maneuver scenarios implied that it was likely MAVEN could last to 2030, as long as necessary maneuver and trajectory planning were started immediately. From the Spacecraft Team and Science Team, it was determined that the potential risks of aerobraking near Deep Dip densities was acceptable. From these conclusions it appeared that the most probable mission scenario would be for MAVEN to aerobrake to ~4500 km apoapsis altitude, support Mars 2020 EDL and provide surface relay support (for the InSight mission), having enough propellant to last to 2030. The appendix presents a further examination of some cases considered in these evaluations.

C. Methodology of Comparison

In evaluating these studies, there was a clear trade-off between science and relay return and the results that came from them. A methodology is described below for evaluating these myriad choices and choosing the most optimal set.

Options that maximized preservation of MAVEN's science were fundamentally in conflict with those that maximized MAVEN's utility as a relay asset for landers on Mars's surface. As with any such trade, there were hypothetically many options that could simultaneously make science and relay quality worse. Among the many design variables available for tradeoffs were (1) how much longer MAVEN would remain in its original Nominal Science Orbit (NSO) prior to aerobraking; (2) how many more Deep Dips (DD) MAVEN would perform prior to aerobraking; (3) how much to reduce MAVEN's apoapsis; and (4) when to raise MAVEN's periapsis "out of the atmosphere" for improved relay predictions. Among many constraints on these trades were (1) aerobraking had to occur after Insight landing and avoid periods of harsh eclipses; (2) aerobraking and subsequent orbit phasing must be completed well prior to Mars 2020's landing; (3) MAVEN must preserve enough fuel for operations to continue to at least 2030.

By defining a simplified version of the trade space, the project could use a mixed-integer linear program to define a Pareto Frontier, which is the boundary of the set of all possible choices that forms the set of "best compromises" between science and relay quality. Figure 6 shows one example of this analysis. Each axis represents a metric that is a linear combination of the design variables. The vertical axis is a normalized metric on science quality, and the horizontal axis is a normalized metric on relay quality. Each red circle plotted on these axes represents a feasible solution that satisfies all the constraints. The blue trace is the frontier of Pareto-optimal design choices. Red circles to the left and below the Pareto front are suboptimal in the sense that there exist solutions that are, for example, just as good for science, but better for relay, and vice versa. Because some of the design variables are integers, such as the number of Deep Dips to perform, there does not exist a continuum of solutions, but instead there are discrete families of solutions; within each family there can be a continuous variation among the real design variables. In this example, there are five distinct "break points" along the Pareto Front highlighted, which represent equally "optimal" solutions.

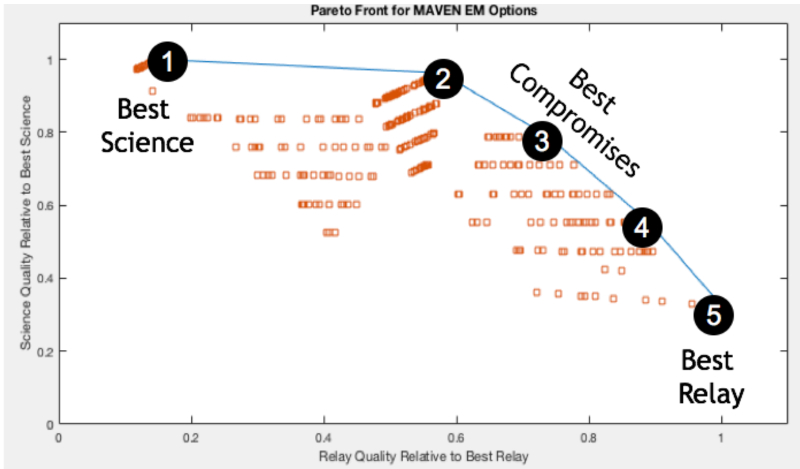

Fig. 6 Pareto Frontier of MAVEN Science / Relay Option Trade Space

Although these results did not directly lead to the final decision to aerobrake MAVEN into a ~4500 × 210 km altitude orbit, they did help to clarify the thinking of the MAVEN leadership team, and helped steer analysis efforts away from exploring suboptimal options interior to the Pareto boundary.

D. Conclusions

These studies were refined in 2018. The expected trade space of mission options was pruned considerably. Concerns about spacecraft power and battery charging in the smaller post-aerobraking orbit were investigated. From this came constraints on when the aerobraking campaign could occur, along with constraints on relay support during the smaller post-aerobraking MAVEN orbits. A number of key conclusions emerged out of this work. Final requirements for the MAVEN mission as determined by MPO through negotiations with MAVEN and Mars 2020 were given in 2018 and included:

1) MAVEN would support Mars 2020 EDL.
2) MAVEN would be expected to last to at least 2030.
3) MAVEN would aerobrake down to an apoapsis altitude between 4000 – 4500 km at M2020 EDL (the range in apoapsis necessary for targeting M2020 EDL).
4) MAVEN would be available to support the InSight lander Instrument Deployment Phase (11/26/2018 to 2/28/2019).[†]
5) MAVEN would increase its periapsis altitude to at least 180 km, optionally increasing it further after Mars 2020 EDL.

With the large trade space narrowed down to the mission scenario stated above, Navigation started to work closely with Mars 2020 on the refinement of the predicted MAVEN trajectories at Mars 2020 EDL. This work is the subject of the rest of this paper.

V. Analytical Determination and Preliminary Evaluation of Mission Options

A. Preliminary Analytical Design Process

The evaluation of the trade space for this optimization search was an important part of this systems analysis. Coming up with a preliminary set of costing for the many cases considered was important as a precursor to more detailed study for specific cases. Some costs and event timings could be derived from orbital mechanics, such as inclination change

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[†] This support requirement would be relaxed later to allow for an early start to aerobraking (see below).

and phasing maneuver costs. However, the complex combination of multiple trajectory modification event timings and the overall very large trade space of future mission timeline options required a preliminary design tool that could propagate MAVEN's trajectory and examine variations rapidly. It used the following approach to propagate MAVEN's trajectory:

1. Effect of J_2 and J_3 on Satellite Orbits

The preliminary design tool performs a simple orbit propagation from one periapsis to the next using the J_2 and J_3 terms and the variation of parameters method [8]. Only these terms were included because they are the primary long-term secular gravity terms that affect the periapsis altitude and plane of the orbit. Higher order spherical harmonics lead to short term, pseudo-random variations in the altitude that are not important for this kind of preliminary study. Performing an expansion from Ref. [8]. gives the mean variation of the longitude of the node:

$$\frac{\overline{d\Omega}}{dt} = -\frac{3}{2} J_2 \left(\frac{r_{eq}}{p}\right)^2 n \cos i \tag{1}$$

as well as the mean rate of the rotation of the line of apsides:

$$\frac{\overline{d\omega}}{dt} = \frac{3}{4} J_2 \left(\frac{r_{eq}}{p}\right)^2 n \left(5 \cos^2 i - 1\right) \tag{2}$$

and the periapsis altitude shift as:

$$\frac{\overline{dq}}{dt} = -\frac{3}{8} J_3 \frac{r_{eq}^3}{p^2} n \cos \omega \left(5 \sin^2 i \sin^2 \omega - 4 \sin i\right) \tag{3}$$

Given this approach, it is straightforward to propagate orbital elements from periapsis to periapsis by multiplying each term by the orbit period and summing it to the previous value. This can then be propagated by including any deterministic maneuvers and the effects of drag.

2. Effect of Drag on Satellite Orbits

The other main non-propulsive perturbation, drag is applied as an impulse velocity change at periapsis, with a density computed using the MarsGRAM-Simplified (MarsGS) density model. As noted by its authors, "MarsGS is an empirical density model … suitable for initial orbit selection and planetary protection studies of mid-altitude orbiters (i.e. above 200 km altitude)…" [9], with the ratio of drag to density computed from the average over the mission, scaled by the duration of the drag pass.

To briefly summarize the density model [10]:

MarsGS density ρ is given as a function of the height above the specified planet reference ellipsoid *h*, time *t*, and a stochastic parameter *z*, as follows:

$$\rho(h,t,z) = \rho_0 \exp\left[-\frac{h-h_0}{H}\right] D(t) \tag{4}$$

where ρ_0 is the reference density of the model (mass / length^3).

The first term $\exp\left[-\frac{h-h_0}{H}\right]$ is an exponential scale factor as a function of height (*h*), where h_0 is the reference height of the exponential scale factor (length), and *H* is the scale height of the exponential scale factor (length).

The second term *D(t)* is the deterministic scale factor that results from the solar flux variations as a function of time *t* as follows:

$$D(t) = 10\left[A_{11yr} \sin\left(2\pi \frac{t-t_{11yr}}{T_{11yr}}\right) - A_{\text{ANN}} \sin\left(2\pi \frac{t-t_{\text{ANN}}}{T_{\text{ANN}}}\right)\right] \tag{5}$$

where:

1) A_{11yr} = Amplitude of the 11-year term (nominally 0.35).
2) T_{11yr} = Period of the 11-year term (nominally 4014.1 days).
3) t_{11yr} = Reference Epoch of the 11-year term (nominally 1 September 1998 – 00:00:00 ET).
4) A_{ANN} = Amplitude of the Martian annual term (nominally 0.2).
5) T_{ANN} = Period of the Martian annual term (nominally 686.98 days).
6) t_{ANN} = Reference Epoch of the Martian annual term (nominally 27 June 1998 – 12:00:00 ET).

3. Additional Changes to Satellite Orbits

From these two primary planetary effects on the spacecraft orbital trajectory, additional changes are added to perturb this trajectory. Periapsis, apoapsis, and inclination change maneuvers are applied as impulsive changes to the orbital elements of an idealized two-body orbit. From the sum of these effects and additional changes an initial low-fidelity trajectory could be estimated and initial costs and event timings could be derived for the orbit and corresponding major trajectory change timelines.

B. Revised Solution Parameters and Derivation and Propagation of Cases

The preliminary design tool produced a set of parameters for analysis of a given case study. The design tool output included results for atmospheric density, heating and dynamic pressure, complete orbital parameters, including periapsis and apoapsis altitude, orbital inclination (i), as well as spacecraft propellant, and Mars 2020 relay geometry and targeting. This approach allowed for the easy examination of different options to satisfy various requirements and targets. It allowed an examination of what penalties might occur, depending on the parameters chosen. It also provided an excellent means for the selection of maneuvers, maneuver timings, and aerobraking parameters. The preliminary design tool served for a first pass of how MAVEN might conduct its future mission plans.

These preliminary studies clarified that there were difficulties and tradeoffs in meeting the desired design goals. As noted, some option groups could meet these goals, but these would require cancelling multiple Deep Dips, and raising the periapsis altitude earlier. Such strategies would have had a great impact on mission science.

Final plans for the MAVEN mission involved analyses using the preliminary design tool to evaluate the ΔV budget studies seen in Section IV. From these ΔV budget studies the preliminary design tool could be used to examine these cases in more detail and provide more accurate ΔV costs on select cases. Sample costs could be examined with the preliminary design tool to evaluate various optional mission plans. Table 2 shows a selection of cases from this effort, looking at mission lifetime and EDL support options.

Table 2 Lifetime & EDL Support Case Studies from Preliminary Variational Analysis

	Case	Mission Through	Transition Higher Orbit	Inc (deg)	Peri Alt (km)	Apo Alt (km)	Cancelled Deep Dips	EDL Cost (m/s)
1	Baseline, no EDL Support	2025	1/1/20	74.23	225	6525		
		2028	11/1/18	74.23	225	6600		
		2030	7/1/18	74.23	225	6625	10	
2	Reduced PCM (48 m/s), no EDL Support	2025	9/1/20	74.23	225	6050		
		2028	8/1/19	74.23	225	6150		
		2030	9/1/18	74.23	225	6210		
3	Reduced PCM (48 m/s), EDL Support	2025	6/1/19	73.63	225	6650		57
		2025	1/1/20	74.93	225	6050		27
		2025	8/1/20	74.93	225	6050	10	19
		2028	7/1/19	74.93	225	5980		19
		2028	11/1/19	74.93	225	6000	10	27
		2030	11/1/18	74.93	225	5950	10	34
4	Reduced PCM (48 m/s), EDL Support 500 km EOM	2025	6/1/19	74.93	225	5970	10 (?)	29
		2028	8/1/18	74.83	225	5930	10 (9)	35
		2030	10/1/17	73.73	225	6580	8,9,10	14

From these studies, the expected trade space of mission choices was pruned considerably. An approach was worked for the future MAVEN mission plan. The approach for the future MAVEN mission plan was broken down into four phases that would be examined in detail:

1) Nominal Science Orbit (NSO) and orbital inclination change: This phase serves as the stem for all further phases, starting from an orbit determination solution through orbit maintenance operations, associated Deep Dips, and orbital fine tuning of the periapsis, to encompassing significant changes to orbital inclination.
2) Aerobraking (AB): This phase takes the MAVEN spacecraft through aerobraking operations to lower apoapsis to the above altitude objectives for operations. (Then continued in an atmospheric science mode.)
3) Periapsis raise: The change of the orbit to Science Relay Orbit (SRO) parameters in support of surface relay.
4) Phasing: the change of MAVEN's true anomaly to support Mars 2020 EDL in the Phased-SRO (PSRO).

In these phases the timing and magnitude of key events, especially major trajectory modifications were evaluated to determine optimal results for both relay support and science return.

The following were planned maneuvers in these phases in support of these goals:

1) Only a total of 9 Deep Dips (which had already been conducted) would be executed
2) The final PCM would be decreased to save propellant, target special science opportunities, and synchronize the orbit with Mars 2020 EDL.
3) An ICM would be executed to help synchronize the orbit with Mars 2020 EDL.
4) Aerobraking would serve as a "free maneuver" to synchronize the orbit with Mars 2020 EDL.
5) The periapsis raise maneuver would put MAVEN in its final higher SRO and correct inaccuracies in the orbit synchronization with Mars 2020 EDL.

These phases are discussed in more detail, covering the final mission plans, and include actual results from completed events.

1. Nominal Science Orbit to Aerobraking

The first of the reference trajectory phases (Fig. 7), the NSO initial state is discussed in Section III. The NSO comprised the majority of the science gathering phases of the mission. Satisfying these science objectives represented the majority of operational concerns.

The first changes to MAVEN's orbit to support the surface relay requirements occurred as MAVEN continued its NSO atmospheric survey – in response to the twin goals of keeping the science community supplied with ongoing atmospheric science while moving to its relay orbit as efficiently as possible. Initial analysis showed that optimal EDL relay would best be accomplished by increasing the inclination of the orbit by more than half a degree (~0.65°) during the NSO.

After examination of several mission plans, Navigation decided to implement an Inclination Change Maneuver (ICM). Such plane change maneuvers are usually very expensive, being of order (for approximately circular orbits):

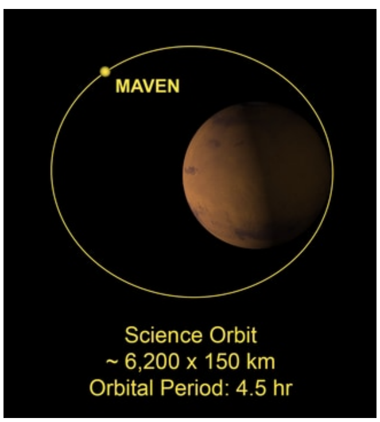


Fig. 7 Nominal Science Orbit

$$\Delta V = 2v_{orbit} \sin\left(\frac{\Delta i}{2}\right). \quad (7)$$

From initial examination, the desired ICM was in the range of 18-20 m/sec of ΔV. Later updates took into account Martian (gravitational) mass concentrations and so the ICM was increased slightly to +0.68°. The final size of the ICM, 19.2 m/sec, agreed well with the initial estimate. Fortunately, this maneuver which had to be undertaken early on for synchronization, was one that did not impact the science gathering of the NSO (it actually brought the inclination closer to the original MAVEN requirements).

2. Aerobraking

At the conclusion of the Nominal Science Orbit, it was decided to have a significant trajectory change to meet the requirements to lower the orbital apoapsis by ~1500 km for surface relay support and Mars 2020 EDL. This change required some innovation. As noted, one of the other requirements for the MAVEN mission was to have sufficient propellant to continue operations through 2030. Conducting a maneuver to lower the apoapsis to such a degree (estimated at 102 m/sec ΔV [11]) would make continuing operations through 2030 very difficult.

Although not designed for it, this objective could be most efficiently met by a 'shallow' aerobraking campaign (Fig. 8). This two to three-month campaign would be an extended atmospheric Deep Dip that would provide a significant science return in this deeper atmospheric region. The aerobraking density corridor of 2.0 – 5.5 kg/km^3 was similar to the Deep Dip corridor, except that the high-density limit was increased. As an additional advantage, this would serve as an excellent climax to the Nominal Science mission This would be a deep survey of the atmosphere at some of the highest atmospheric densities for more than two months – several times the length of nominal Deep Dip studies.

Fig. 8 Aerobraking

Although this approach offered several benefits, constraints became apparent after further study. First, the post-aerobraking orbit, with a much shorter period of 3.6 hours, would significantly increase strain on the battery because larger portions of the orbit were in eclipse. From this concern the additional constraint was added to avoid the May 2019 timeframe where lengthy eclipse seasons were predicted. This constraint prompted studies examining how steeply down the atmospheric glide slope [11] the spacecraft could fly. Additionally, after further examination, MPO decided that support requirements to provide relay support during the Insight lander Instrument Deployment Phase could be relaxed, allowing the aerobraking campaign to start two weeks earlier, on 11 February 2019. From diligent and aggressive work on the part of the MAVEN Navigation Team, the aerobraking campaign actually concluded on 5 April 2019, more than a month earlier than expected, having expended only 6.8 kg of fuel, (14.8 m/sec ΔV) out of a budgeted 12.5 kg.

This phase of the mission in these reference trajectories continued past the actual aerobraking operations, and would comprise the majority of the rest of the mission's atmospheric science studies, as the periapsis remained near its nominal ~150 km. For mission planning purposes outside of these studies, this post-aerobraking period would be termed the eXtended Science Orbit (XSO). It allowed further science until the periapsis would be raised to the ~180 km minimum altitude of the Science Relay Orbit as discussed below.

3. Periapsis Raise to Science Relay Orbit

After the aerobraking campaign, the mission enters the last phase of its system of orbital changes. This involves the raising of the periapsis from its NSO (and XSO) nominal altitude of ~150 km to ~210 km (180 km minimum altitude) to move the spacecraft out of most of the atmospheric drag during periapsis (Fig. 9). This Science Relay Orbit (SRO) would also decrease atmospheric science returns. This periapsis altitude would naturally oscillate by ~60 km due to Mars J_3 gravity effects. The reduction in periapsis density and the lack of corridor control maneuvers allowed for much better Navigation prediction accuracy for lander relay planning. It also dramatically reduced propellant usage, thereby extending the mission lifetime.

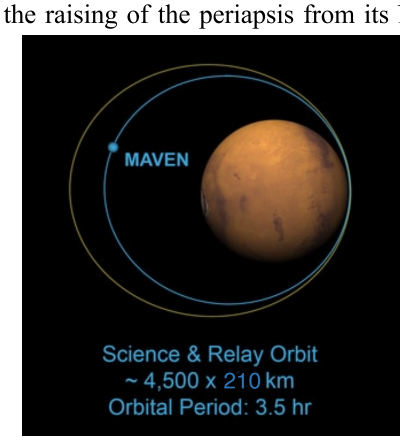


Fig. 9 Science Relay Orbit

The major event of this mission phase would be the significant maneuver to raise the periapsis. Originally planned for April 2020, the project decided to postpone the maneuver five months to September 2020, gaining five months of improved science, after analysis showed that Mars J_3 gravity effects would naturally raise the periapsis. This decision would be another instance of using clever planning to achieve several effects.

4. Phasing of Science Relay Orbit Trajectory

One final act of fine tuning would be required to fully support Mars 2020 EDL operations. Although the orbit would have the size and placement to support surface relay operations, the spacecraft's phasing along that orbital path would need to be modified. The Mars 2020 landing targets are shown in Fig. 10 below. To modify the spacecraft position, a phasing maneuver would change the time of the arrival of the spacecraft over the landing site of Mars 2020. Such a maneuver would have a magnitude:

$$\Delta V = \frac{\Delta Ph \, Gm_{\sigma}^{3/2}}{6\Pi v_{orbit} a^{5/2}} \tag{8}$$

where *ΔPh* is the desired change of arrival-time. In actual practice, this would comprise several smaller maneuvers, but in the study only one such maneuver was designed.

All of the Mars 2020 potential landing sites were clustered near Jezero Crater or Columbia Hills. Unfortunately, MAVEN had to start performing maneuvers for synchronizing its orbit with Mars 2020 EDL before the landing site was chosen. A strategy was designed which would put MAVEN's orbit in a location which would support either of these two landing sites. This would allow for final phasing maneuvers to put MAVEN in the correct location for the appropriate landing site. The Mars 2020 Science team chose Jezero crater as its landing site in October 2018, allowing MAVEN to focus in its work on this single location.

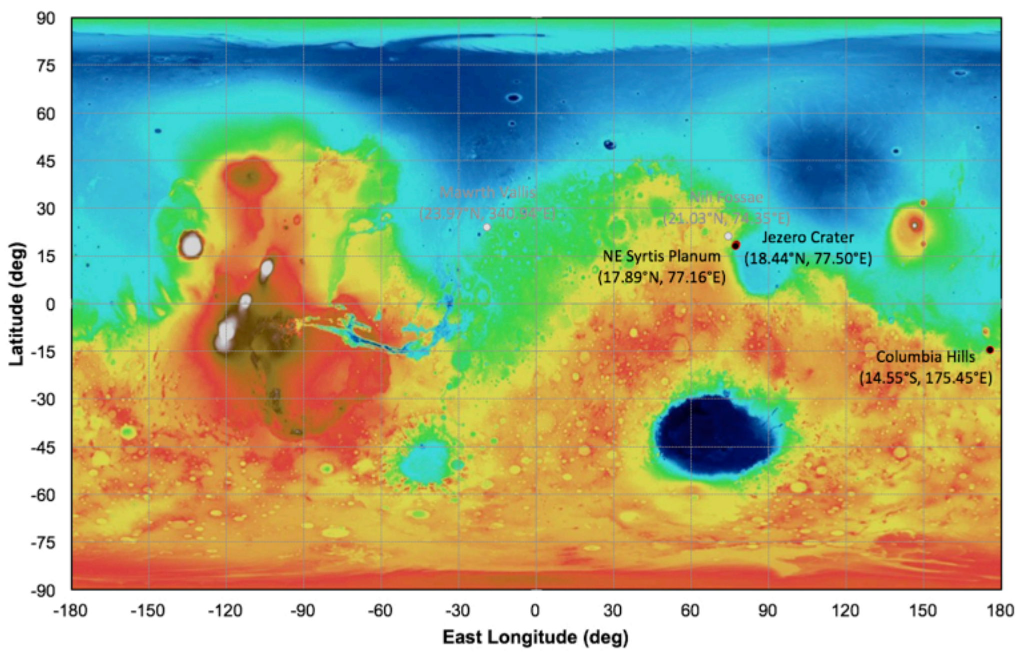


Fig. 10 Jezero Crater and Columbia Hills Landing Sites Shown Against Martian Topographic Map

From the *a priori* values for spacecraft phasing given by Eq. 8, an iterative process fine-tuned a phasing maneuver. As the maneuver is particularly sensitive to the initial state, its parameters continue to evolve. The current ΔV (as of this writing) is 0.27 m/sec for September 2020.

Given the operational phases above, we used the MONTE software set [9] to conduct long range propagation of MAVEN spacecraft trajectories. High resolution models of the Martian atmosphere and its seasonal variation (Mars-GRAM 2005 map year 0 – referred to in this paper as MarsGRAM-2005) [12], Martian oblateness, and gravitational perturbations from Phobos, Deimos, and the other planets were used in the integration of these detailed reference trajectories. These results are discussed in the next section.

VI. Results from Reference Trajectory Solutions

A selection of reference trajectories is presented from three different times in the examination of differing trajectories for the MAVEN mission plan. The intent is to give perspective on the process of tuning and fine tuning a spacecraft trajectory to evaluate a given set of conditions. Both the preliminary design tool and MONTE with MarsGRAM-2005 are used. Figure 21 at the end of this section shows select results from these three major runs and are compared in Table 3. The final targeting results for Mars 2020 EDL are shown in Tables 4-6.

Table 3 Reference Trajectory Results Summarized

Reference Trajectory	*A Priori*	2 March 2018	*A Priori*	22 May 2018	11 April 2019	Actual
NSO: ICM – ΔV	18.1 m/sec	18.1 m/sec	19.2 m/sec	19.2 m/sec	19.26 m/sec	19.26 m/sec
NSO: PCM – ΔV	7.1 m/sec	7.5 m/sec	9.97 m/sec	10.1 m/sec	10.07 m/sec	10.07 m/sec
AB: Time – days	69.9 days	64.1 days	61.7 days	61.4 days	51.1 days	51.1 days
AB: Control – ΔV	14.1 m/sec	11.8 m/sec	14.1 m/sec	11.6 m/sec	8.9 m/sec	8.9 m/sec
SRO: PRM – ΔV	8.7 m/sec	8.72 m/sec	8.8 m/sec	8.72 m/sec	4.92 m/sec	
PSRO: PHASE – ΔV	n/a	0.16 m/sec	n/a	0.18 m/sec	0.27 m/sec	

All prior executed trajectory changes are shaded yellow (at the time of publication).

A. 2 March 2018 – Reference Trajectory

1. Preliminary Reference Trajectory Case Study

A preliminary run, with a simplified perturbation model as described in Section V, established a "standard case" for the extended mission plan. This analysis provided a feasible set of initial values for a more detailed trajectory propagation run which would lay out the component parts that would be used in later Reference Trajectories. We could then use the MONTE trajectory propagation toolset and MarsGRAM-2005 to refine these event times and target values in higher fidelity studies for each of the phases.

The differences in execution time between the simple and thorough models showed the value of the dual approach: while the preliminary design tool could generate a new low fidelity trajectory for a different set of event timings and targets on the order of five to ten minutes on a moderately fast laptop, the higher fidelity trajectory generation with full atmospheric modeling would take anywhere from 10 to 24 hours of runtime on the fastest systems, with most of the run time large spent on aerobraking trajectory modeling. The trajectories were propagated from 5 February 2018, with the low fidelity propagation to 2030, and the higher fidelity trajectory propagation running several months past Mars 2020 EDL.

Preliminary targeting approaches and the full reference trajectory runout included:

Nominal Science Orbit (NSO) phase (5 February, 2018, to 19 March, 2019):

1) ICM on 25 July 2018 of 18.1 m/sec to increase orbital inclination by +0.65°.
2) PCM on 23 May 2018 of 7.5 m/sec for orbit period (apoapsis altitude) maintenance. (Refined in the reference trajectory to 7.1 m/sec.)
3) Deep Dip #9 running from 25 April 2018 to 3 May 2018 with a total of 16.6 m/sec. of estimated maneuvers. (Refined in the reference trajectory to 8.6 m/sec.)
4) Outside of the short Deep Dip activity, the trajectory was constrained through OTMs to fly in an atmospheric density corridor of 0.05-0.15 kg/km^3 for the NSO, as noted above.

Aerobraking (AB) phase:

1) Aerobraking campaign running from 5 March 2019 to 15 May 2019 for a total of 69.9 days, atmospheric density corridor of 2.0 – 5.5 kg/km^3, target apoapsis 4575 km altitude (Examined repeatedly to shorten and fine-tuning the campaign in the reference trajectory to 5 March 2019 to 10 May 2019 for a total of 64.1 days.)
2) Aerobraking control maneuvers, including entry and exit of aerobraking corridor of 14.1 m/sec. (Refined in the reference trajectory to 12 estimated aerobraking control maneuvers, including entry and exit of aerobraking corridor of 11.8 m/sec.)
3) A continuance of the atmospheric science in the atmospheric corridor, termed the eXtended Science Orbit (XSO).

Science Relay Orbit (SRO) phase (propagated from 1 May 2020 to 12 May 2021):

1) End of XSO atmospheric science 6 May 2020.
2) Periapsis raise maneuver on 6 May 2020 of 8.7 m/sec with a target periapsis of ~200 km minimum altitude (Refined in the reference trajectory to 7.1 m/sec.)

Phased Science Relay Orbit (PSRO) Reference Trajectory (propagated from 1 October 2020 to 12 May 2021):

The last reference trajectory case examines the detailed requirements to support Mars 2020 EDL operations. This task has no analog in the preliminary design. It corrects any offsets in the MAVEN phasing with EDL, placing the MAVEN spacecraft along its orbit so that it is in the right part of its orbit to be overhead during Mars 2020 EDL. The MAVEN orbiter, at the moment of touchdown must be at least 10° above the local horizon at a slant range of no more than 3000 km. This new trajectory replaces the overlapped SRO trajectory between 1 October 2020 and 12 May 2021. The phasing maneuver, 0.16 m/sec on 20 October 2020, targets the landing of Mars 2020, to a final target of 2249.12 km slant range and only 7.04 seconds late. This target is compared against both Columbia Hills and Jezero Crater landing sites, as shown in Table 4, which can be met by perturbing the spacecraft to slightly different phasing.

Table 4 Columbia Hills and Jezero Crater Mars 2020 EDL Phase Position (PSRO)

Trajectory	Time	Lat, deg	Long, deg	Range, km
Columbia Hills (PSRO):				
Target	18-FEB-2021 13:19:13.1852 ET	-14.57000	175.44000	2600.000
Predict EDL	18-FEB-2021 13:19:13.1852 ET	-18.85639	-168.87531	1622.167
Timing Error: '00:03.948677281 TAI' or 3.9487 sec (Late)				
Jezero Crater (PSRO):				
Target	18-FEB-2021 20:32:47.1852 ET	18.44000	77.50000	2600.000
Predict EDL	18-FEB-2021 20:32:47.1852 ET	4.30905	78.75046	2249.123
Timing Error: '00:07.040125505 TAI' or 7.0401 sec (Late)				

B. 22 May 2018 – Reference Trajectory

1. A Priori *Analytical Solutions*

The first reference trajectory where information was available to account for all remaining MAVEN mission trajectory perturbing events, this allowed for a propagation against a known set of target characteristics. In this reference trajectory the final Deep Dip had been performed and a post Deep Dip period maintenance maneuver had been planned (PCM). A preliminary design analytical run established good target values that would be used later in more detailed trajectory propagation runs. The trajectories were propagated from 16 May 2018, with the low fidelity propagation to 2030, and the higher fidelity trajectory propagation running several months past EDL. Detailed examination of orbital characteristics is included.

Initial targeting approaches for this reference trajectory:

NSO phase:

1) ICM on 25 July 2018 of 19.2 m/sec to increase orbital inclination by +0.68°. Updated from the previous reference trajectory to account for Martian (gravitational) mass concentrations.
2) PCM on 23 May 2018 of 9.97 m/sec for orbit period (apoapsis altitude) maintenance.
3) MAVEN would be constrained through minor flight path control maneuvers to fly in its nominal science atmospheric density corridor of 0.05-0.15 kg/km^3 for the duration of the NSO.

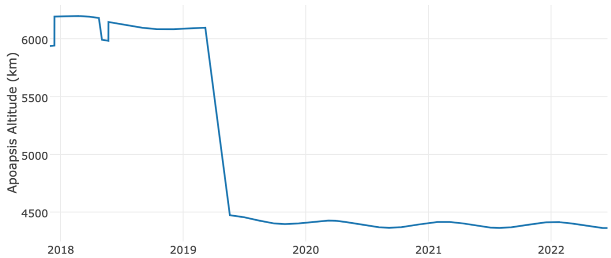
AB phase:

1) Aerobraking campaign running from 5 March 2019 to 6 May 2019 for a total of 61.7 days, atmospheric density corridor of 2.0 – 5.5 kg/km^3, target apoapsis 4505 km altitude.
2) Aerobraking control maneuvers of 14.1 m/sec, including entry and exit of the aerobraking corridor.
3) A continuance of the atmospheric science (XSO).

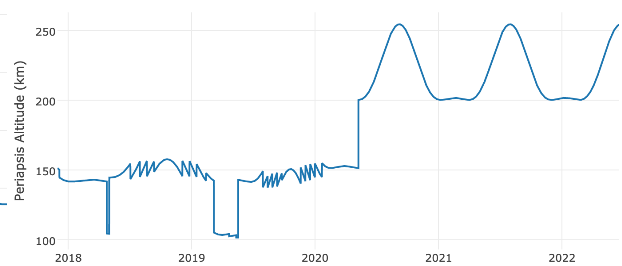
SRO phase:

1) End of XSO atmospheric science on 6 May 2020.
2) Periapsis raise maneuver on 6 May 2020 of 8.8 m/sec with a target periapsis of ~200 km minimum altitude.

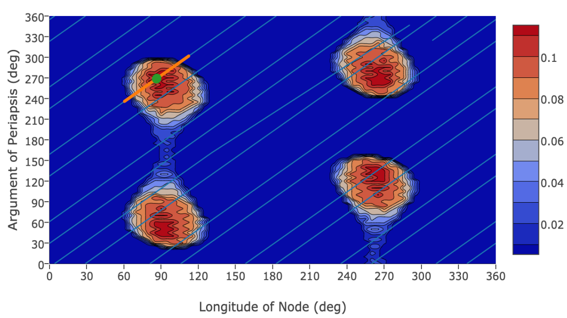
These targets produced a preliminary trajectory with further improved altitude characteristics, and landing overflight and communications visibility for the primary (Jezero Crater) landing site. Figure 11 presents the periapsis and apoapsis altitudes as well as the Mars 2020 EDL orbital overflight percentage (the amount of time in its orbit the MAVEN spacecraft will be in a position for relay), and the relay communication geometry.



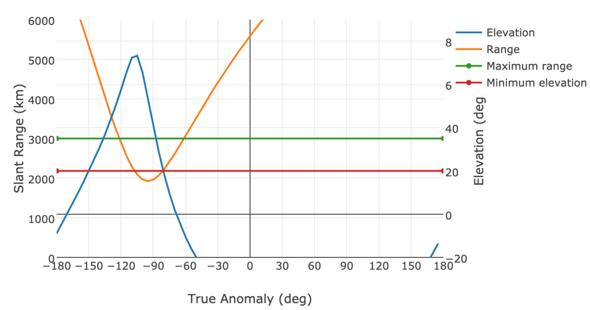
a) Apoapsis Altitude – Preliminary



b) Periapsis Altitude – Preliminary



c) Mars 2020 Orbital Overflight Percentage



d) Mars 2020 Communications Geometry

Fig. 11 Preliminary Orbital Parameters and Communications Summary

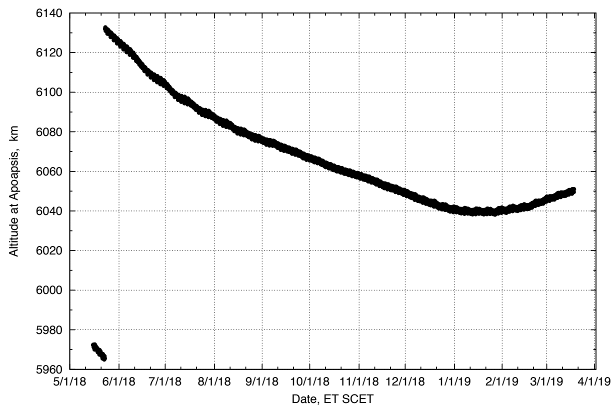
With these results, time could be spent refining these event timings and target values in higher fidelity studies with the MONTE trajectory propagation toolset and the MarsGRAM-2005 Martian atmospheric models.

2. Nominal Science Orbit (NSO) Reference Trajectory

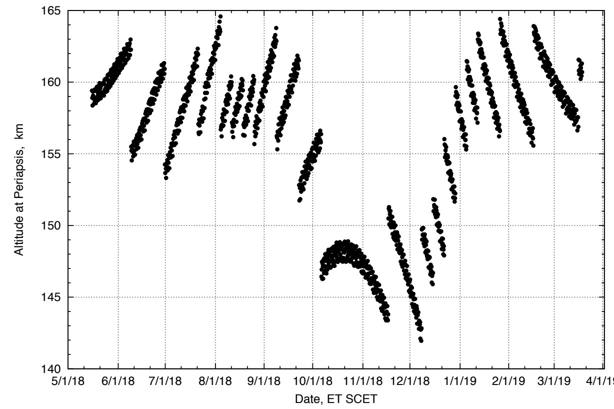
From these revised values a full run covering the NSO was generated, propagating the trajectory over the period from 16 May 2018, to 19 March 2019. The *a priori* values given by the preliminary design tool were refined by this more detailed analysis to produce the following fine-tuned targeted values:

1) ICM on 25 July 2018 of 19.2 m/sec to increase orbital inclination by +0.68°. Updated from the previous reference trajectory to account for Martian (gravitational) mass concentrations.
2) PCM on 23 May 2018 of 10.1 m/sec for orbit period (apoapsis altitude) maintenance.
3) MAVEN would be constrained through minor flight path control maneuvers to fly in its nominal atmospheric density corridor for the duration of the NSO.

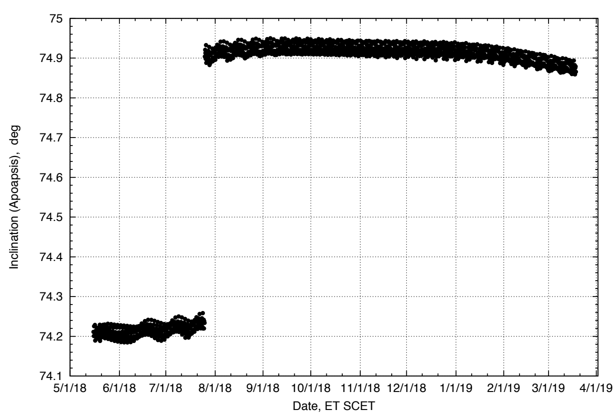
High fidelity propagations of the spacecraft trajectory produced a much more detailed study of the spacecraft orbital altitude over time. (Likewise these charts are at a much higher resolution than the preliminary study above.) The plots also show the inclination change of 25 July 2018 (Fig. 12).



a) NSO Apoapsis Altitude



b) NSO Periapsis Altitude



c) NSO Inclination Change from ICM-1

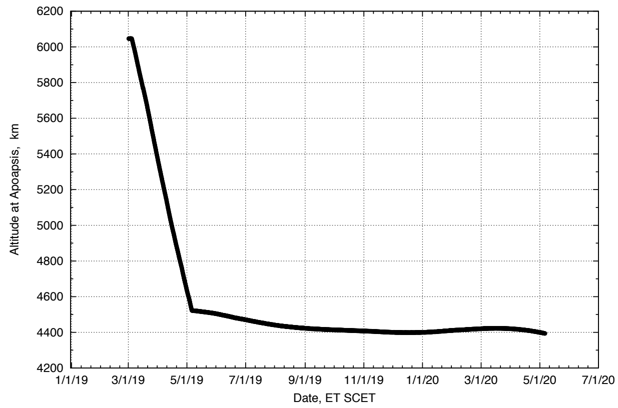
Fig. 12 NSO Orbit Altitude and Inclination – High Fidelity

3. Aerobraking (AB) Reference Trajectory

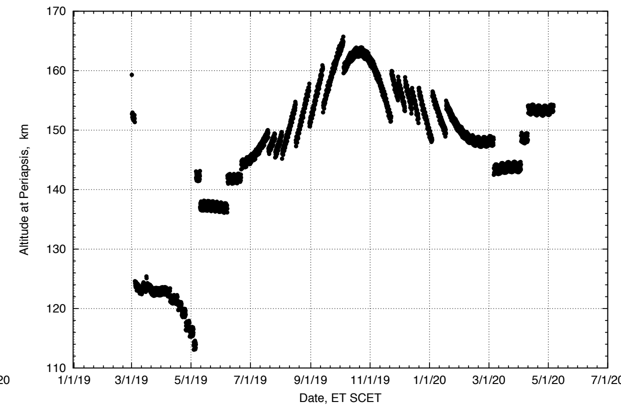
Initiated from the NSO's trajectory, and using the *a priori* values from the preliminary design tool, this trajectory was propagated from 1 March 2019 to 7 May 2020 in high fidelity. Overlapping with the previous NSO trajectory by 19 days, this was by far the most computationally intensive study, as the full MarsGRAM-2005 density profile was expensive to model for a spacecraft which goes through multiple periapsis every day into the deeper atmosphere. This study was re-run through many differing cases. Several increasingly steep aerobraking campaigns were considered to promote an early end to the aerobraking campaign due to concerns about the extensive eclipse season that would occur in May of 2019. *A priori* values given by the preliminary design tool were significantly refined by the more detailed models available:

1) The aerobraking campaign was examined repeatedly to shorten and fine-tuning the campaign, from 5 March 2019 to 6 May 2019 for a total of 61.4 days, with a target apoapsis of 4505 km altitude.
2) 9 aerobraking control maneuvers, including entry and exit of the aerobraking corridor, for a total of 11.6 m/sec.
3) During the XSO after aerobraking, MAVEN would be constrained through OTMs to fly in the Nominal atmospheric density corridor. This strategy allowed continued atmospheric science return until the periapsis raise maneuver of the SRO.

As with the NSO orbit, the MONTE software produced much higher fidelity spacecraft trajectories with a much higher resolution of the spacecraft altitude over time (Fig. 13). Further concern was given to the steeper aerobraking campaign's atmospheric density and spacecraft stresses (Fig. 14).

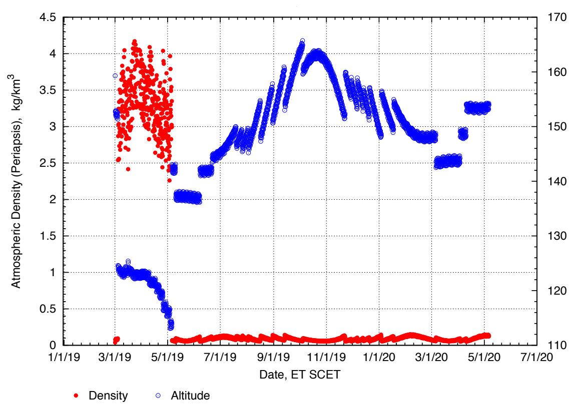


a) Apoapsis Altitude

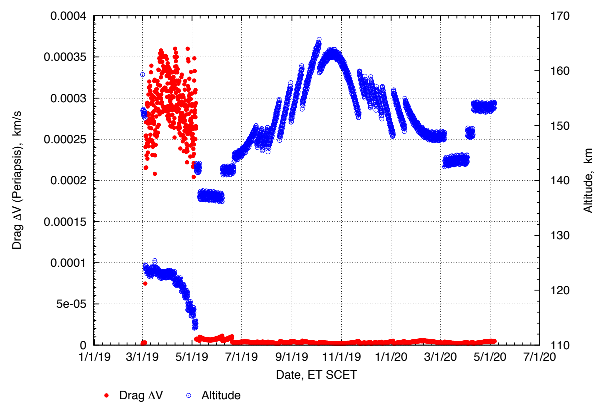


b) Periapsis Altitude

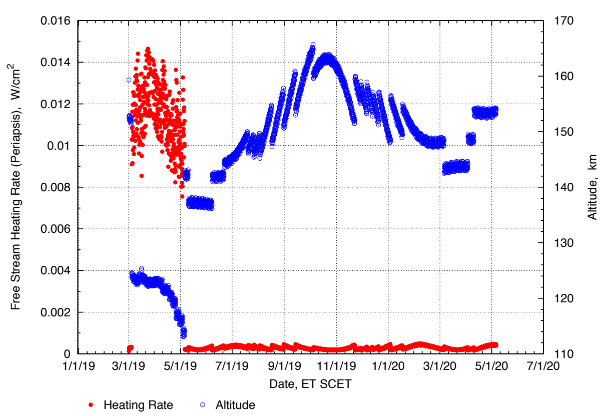
Fig. 13 Aerobraking Altitude



a) Atmospheric Density



b) Atmospheric Drag



c) Spacecraft Free Stream Heating

Fig. 14 Aerobraking Estimated Spacecraft Operational Characteristics

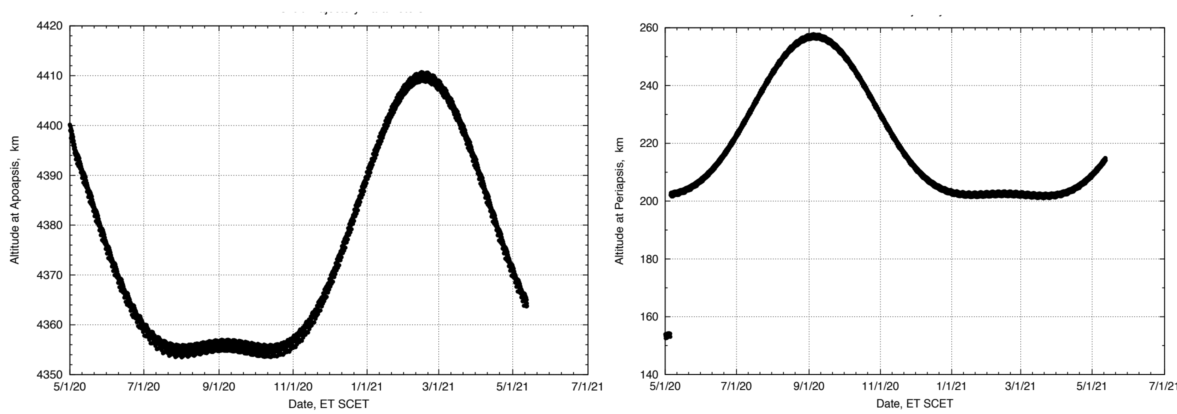
4. Science Relay Orbit (SRO) Reference Trajectory

After aerobraking, the Science Relay Orbit (1 May 2020, to 12 May 2021) will mark the end of most atmospheric science of the MAVEN mission. Overlapping with the previous AB trajectory by seven days in this phase the periapsis of the spacecraft is raised to the final altitude for surface relay support and Mars 2020 EDL. Our detailed analysis used these targeted values:

1) End of XSO atmospheric science 6 May 2020.

2) Periapsis raise maneuver on 6 May 2020 of 8.72 m/sec with a target periapsis of ~200 km minimum altitude.

Unlike the previous phases, this phase is raised above most atmospheric stresses, much more closely resembling the one generated by the preliminary design tool. However much higher fidelity spacecraft trajectories continue to give greater resolution of the spacecraft altitude over time (Fig. 15).

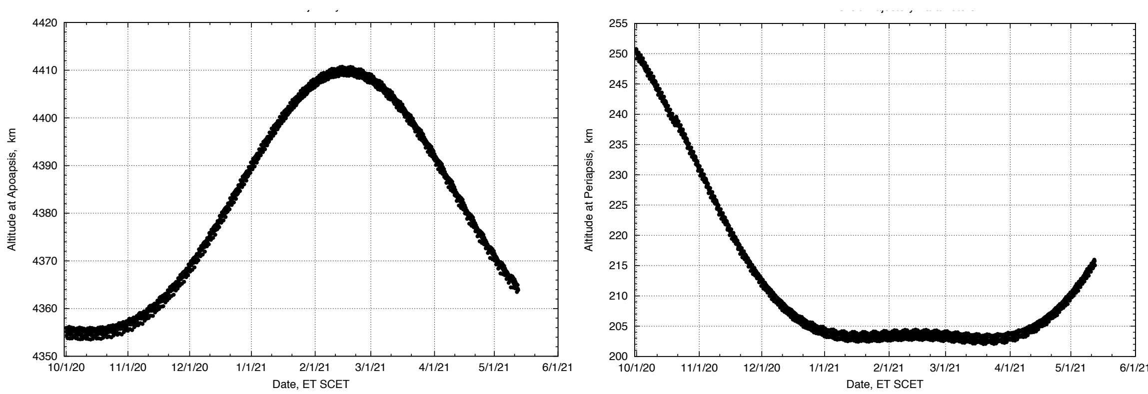


a) SRO Apoapsis Altitude **b) SRO Periapsis Altitude with Periapsis Raise**

Fig. 15 SRO Altitude

5. Phased Science Relay Orbit (PSRO) Reference Trajectory

Our last study in this set examines the detailed requirements to support Mars 2020 EDL. It phases the MAVEN spacecraft with EDL and places MAVEN along its orbit to be overhead during the entry through landing of Mars 2020. The MAVEN orbiter, at the moment of touchdown must be at least 10° above the horizon and at a slant range of no more than 2600 km. This new trajectory replaces the overlapped SRO trajectory between 1 October 2020 and 12 May 2021. A single phasing maneuver, on 20 October 2020, of 0.18 m/sec targets the landing of Mars 2020, to a final target of 1951.05 km slant range and 0.46 seconds early, as shown in Table 5. This maneuver does not impact the altitude characteristics of the orbit significantly (Fig. 16) – only the position of the spacecraft, which is compared in high resolution against the targeted landing site at Jezero Crater. (As noted both Columbia Hills and Jezero Crater can be met by the same trajectory with differing phasing). Jezero is considered for this reference trajectory to be the nominal case.



a) SRO (Phased) Apoapsis Altitude **b) SRO (Phased) Periapsis Altitude**

Fig. 16 SRO (Phased) Altitude

Table 5 Jezero Crater Final Mars 2020 EDL Phase Position

Trajectory	Time	Lat,deg	Long,deg	RAAN,deg	APF,deg	Range, km
Jezero Crater (PSRO):						
Target	18-FEB-2021 20:25:47.3728 ET	15.8199	68.5045	87.9953	267.6527	1932.518
Predict Entry	18-FEB-2021 20:25:47.3728 ET	15.8073	68.5067	87.9937	267.6443	1932.166
Timing Error:	'-00:00.456921123 ET' or -0.4569 sec (Early)					

These phased targeting results from this reference trajectory were vetted by Mars 2020 against updated and enhanced landing site criteria (ERTF-1) [13] a month after the release of the reference trajectory, per the schedule in an Operational Interface Agreement for EDL surface relay operations .

C. 11 April 2019 – Reference Trajectory

1. A Priori *analytical solutions*

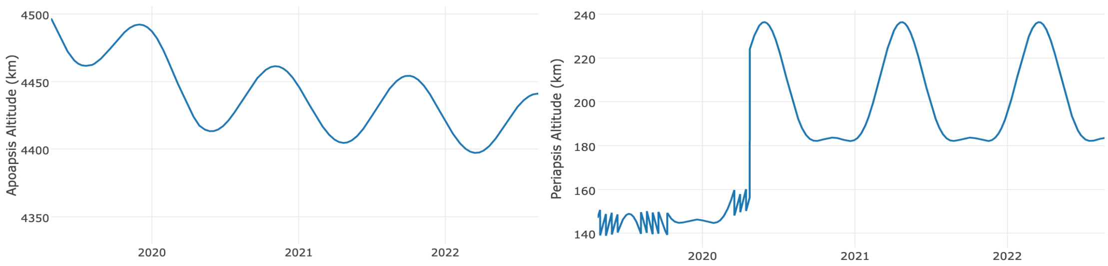
A post-aerobraking reference trajectory delivery was generated for a much more mature case. A preliminary design tool analytical run served to check the *a priori* values. These values however were generated by a prior detailed trajectory propagation designed from Orbit Determination results during the aerobraking campaign. Although a bit circular in design, such targeted values were of much higher resolution than those provided by the preliminary design software. Moreover, this case served to investigate any second order effects due to ending aerobraking a full month earlier than designed. This was propagated after the end of the successful aerobraking campaign from 25 April, 2019, through several months past EDL.

Initial targeting approaches for the Reference Trajectory included:

Post-Aerobraking XSO phase:
This would comprise the remainder of the atmospheric science mission through the Periapsis raise maneuver.
1) MAVEN would be constrained through OTMs to fly in an atmospheric density corridor of 0.05-0.15 kg/km^3 for the duration of the XSO.
2) This would serve as the base trajectory for the rest of the reference trajectory.

SRO phase:
1) End of XSO atmospheric science on 22 April 2020.
2) Periapsis raise maneuver on 22 April 2020 of 4.92 m/sec with a target periapsis of ~180 km minimum altitude.

These targets produced a preliminary trajectory with altitude characteristics, and landing overflight and communications visibility for the primary (Jezero Crater) landing site (Fig. 17).



a) Apoapsis Altitude – Preliminary **b) Periapsis Altitude – Preliminary**

Fig. 17 Preliminary Orbital Parameters

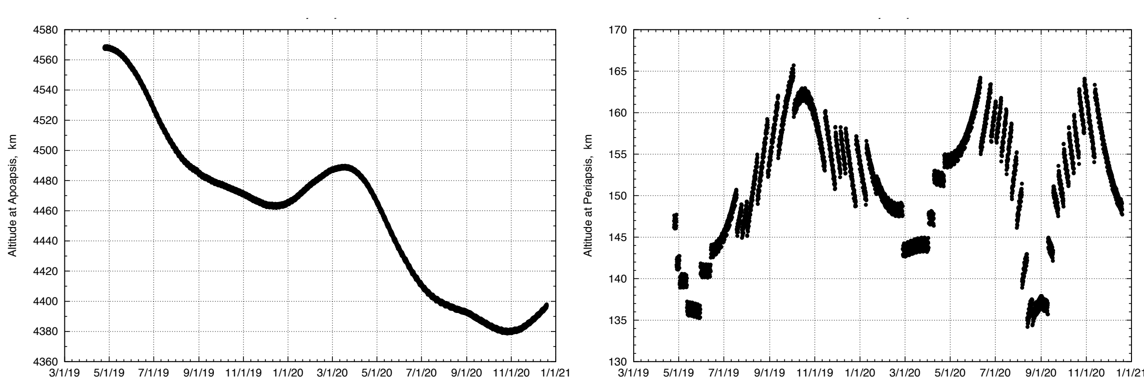
With these results time could be spent refining these event timings and target values in post-aerobraking studies (benefiting from far fewer perturbing influences on the spacecraft) using the MONTE trajectory propagation toolset and the complete MarsGRAM-2005 Martian atmospheric density models.

2. Post-Aerobraking XSO Reference Trajectory

Initiated from a trajectory covering the successful aerobraking campaign. This aerobraking campaign ended with MAVEN at an apoapsis altitude of 4566 km. From the revised values of this aerobraking effort a full trajectory covering the remaining atmospheric science activity and the transition to the SRO was propagated over the period from 25 April 2019 to 20 December 2020. *A priori* values given by prior orbit determination runs, reference trajectories, and the preliminary design tool, were refined by this more detailed analysis to produce the following targeted values and case study:

1) MAVEN would be constrained through minor flight path control maneuvers to fly in an atmospheric density corridor for the XSO up to the periapsis raise maneuver in the SRO. This had a goal of continuing to do MAVEN's atmospheric science for as long as possible (XSO).
2) This would serve as the base trajectory for the rest of the reference trajectory.

This high-fidelity propagation of the spacecraft trajectory produced a much more detailed study of MAVEN's orbital altitude over time and served as the base for the rest of the reference trajectory (Fig. 18).



a) Apoapsis Altitude **b) Post-AB Periapsis Altitude**

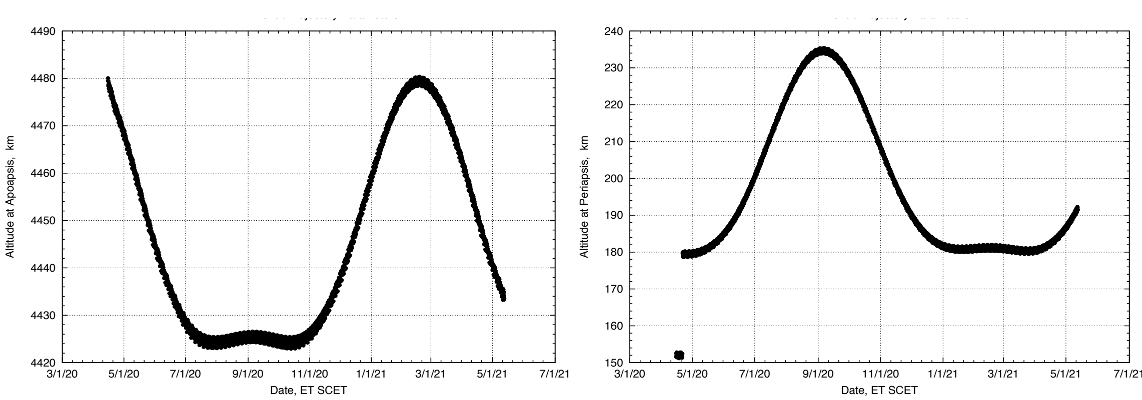
Fig. 18 Post Aerobraking Altitude

3. Science Relay Orbit (SRO) Reference Trajectory

Proceeding from the finalized post-aerobraking XSO trajectory, the Science Relay Orbit will run from 15 April 2020, just after the successful conclusion of the aerobraking campaign, to 12 May 2021. In this phase the periapsis of the spacecraft is raised to the final orbital configuration for surface relay support for the rest of the mission – especially for Mars 2020 EDL. The *a priori* values were further refined by this detailed analysis to produce the following fine-tuned values:

1) End of XSO atmospheric science 22 April 2020.
2) Periapsis raise maneuver on 22 April 2020 of 4.92 m/sec with a target periapsis of ~180 km minimum altitude.

Unlike with the previous phases, this phase much more closely resembles ones generated by the preliminary design tool, due to being raised above most of the atmospheric perturbations. The much higher fidelity spacecraft trajectories give a greater resolution of the spacecraft altitude (Fig. 19).

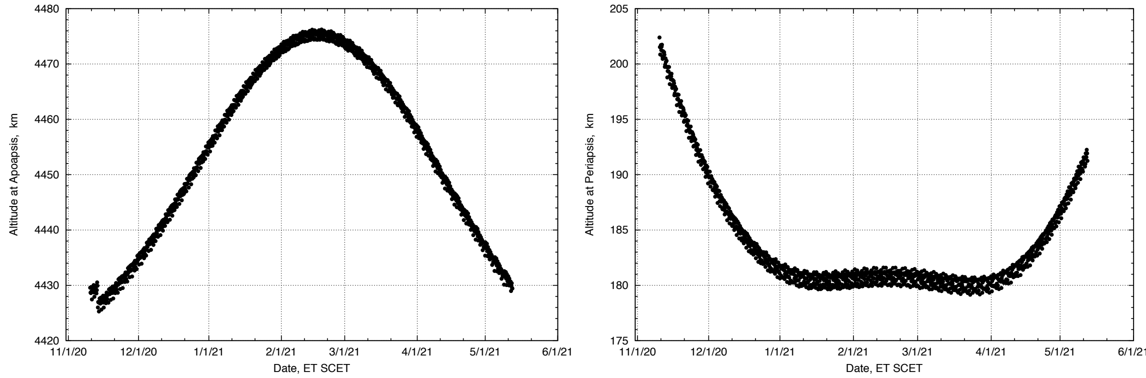


a) SRO Apoapsis Altitude **b) SRO Periapsis Altitude with Periapsis Raise**

Fig. 19 SRO Altitude

4. Phased Science Relay Orbit (PSRO) Reference Trajectory

Overlapping with the Science Relay Orbit, this last study examines the detailed requirements to support Mars 2020 EDL operations, phasing the MAVEN spacecraft along its orbital trajectory so that it is in the right part of its orbit to be overhead during the entry through landing of Mars 2020. As noted, this involves the MAVEN orbiter at the moment of touchdown having a view towards the landing site of at least 10° above the horizon and a revised slant range of no more than 2600 km. Running from 1 October 2020 to 12 May 2021, this replaces the previous trajectory over this period with one with MAVEN phased along its orbit to meet this objective. This phasing maneuver, on 14, November 2020 of 0.27 m/sec, targets Jezero Crater as the landing site for Mars 2020. It targets the landing to a final target of 2062.16 km slant range and 0.39 seconds late. While other phasing maneuvers are expected to fine tune the spacecraft synchronization, they are not planned in this reference trajectory. The perturbation of the orbit does not significantly impact the altitude characteristics of the orbit (Fig. 20) – only the phasing of the spacecraft, which is compared in high resolution (in Table 6) against the targeted landing site chosen for Jezero Crater. These phased targeting results from this reference trajectory were further vetted against updated and further enhanced landing site criteria (ERTF-2) [14] shortly after the release of the reference trajectory by Mars 2020 for EDL surface relay operations (Table 6).



a) SRO (Phased) Apoapsis Altitude **b) SRO (Phased) Periapsis Altitude**

Fig. 20 SRO (Phased) Altitude

Table 6 Jezero Crater Final Mars 2020 EDL Phase Position

Trajectory	Time	Lat,deg	Long,deg	RAAN,deg	APF,deg	Range, km
Jezero Crater (PSRO):						
Target	18-FEB-2021 20:26:42.9550 ET	13.1627	66.3245	85.2889	269.1100	1945.198
Predict Entry	18-FEB-2021 20:26:42.9550 ET	13.1737	66.3215	85.2890	269.1042	1945.252
Timing Error:	'00:00.392373461 ET' or 0.3924 sec (Late)					

D. Finalized Target Plots and Altitude Communications Analysis, with Mars 2020 Mission Review

The phased reference trajectory results were examined by MPO and Mars 2020. Mars 2020 performed detailed examinations over the entire entry through landing period of EDL, comparing MAVEN's geometry relative to Mars 2020 trajectories. From this Mars 2020 calculated EDL surface relay link margins, and then validated the MAVEN trajectories for Mars 2020 EDL surface relay coverage. As a capstone to this examination, Fig. 21 serves as an excellent display of the solutions as they compare to each other.

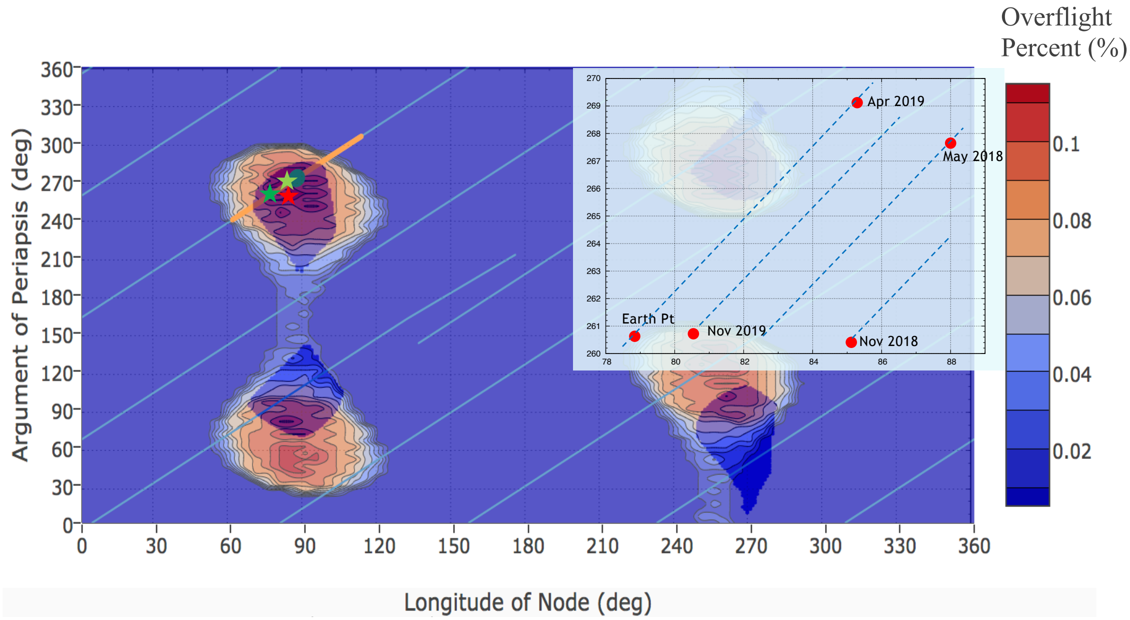


Figure 21 symbols:

- ● 22 May 2018 reference trajectory (above)
- ★ 17 October (November) 2018 (additional study)
- ★ 11 April 2019 reference trajectory (above)
- ★ 11 April 2019 with lower AB exit at 4522 km apoapsis
- ● 20 November 2019 (zoomed in overlay – preliminary study)

Fig. 21 Navigation Design vs. Mars 2020 Hourglass Communications Plot

Figure 21 is an overlay of the "official" Mars 2020 hourglass communication plots over the hourglass plot generated by the MAVEN Navigation preliminary design output. It encapsulates the final optimal results from the studies above. Set up with the results from the Navigation May 2018 preliminary design, this has been updated with the final runout values from several delivered reference trajectories as shown in the key.

The orange nodes (NAV hourglass plots) in Fig. 21 show the expected amount of MAVEN's orbit that will be in an acceptable position for relay. This is based on positions centered one month around EDL for Jezero, derived from the preliminary design, as updated from the given MAVEN reference trajectory deliveries (above). Inclination or out of-plane orbit changes move the light blue lines representing the trajectory "up" and "down" (at an angle) perpendicular to the light blue line. In-plane maneuvers such as apoapsis altitude and phasing (period) changes move the spacecraft overflights along the light blue lines.

The blue nodes (coming from Mars 2020 hourglass communications plots) are from the Mars 2020 mission review, covering both Jezero Crater and Columbia Hills sites. The blue nodes cover all launch days to EDL. The slant range to the trajectory of the relay orbiter in these nodes is under 2600 km and at least 12° above the horizon.

VII. Summary and Conclusions

With its successful trajectory change, MAVEN will be able to provide support for the Mars 2020 relay activities from EDL through surface operations beyond 2030. The analysis performed in this paper illustrate approaches that missions with limited resources and capabilities could potentially benefit from. Such a strategy has allowed the MAVEN mission to retain adequate science return and maintain operational efficiency while satisfying relay and orbit lifetime objectives. This can serve as an excellent example for future missions having similar needs and requirements.

Appendix

As noted in Section IV, many cases were considered in the trade space of options to support the MPO requirements for surface relay support and Mars 2020 EDL. Table 7 presents the 14 major cases considered for this trade study, with the final apoapsis altitude, science return, and ultimate expected mission lifetime for MAVEN.

Table 7 Major Case Studies of Options for MAVEN Surface Relay Support and Mars 2020 EDL

Case	Apoapsis Altitude (km)	Number of Deep Dips after DD-6	Science Return Relative to MAVEN Science Orbit	Aerobraking	EDL Relay Support	Mission Life Through:
Science mission only (no relay)	6,200	4	100%	No	No	2034
Science mission with EDL support only	6,200	4	100%	No	Yes	2030
Science mission full EM-2, 4,500 km apoapsis, and EDL	4,500	4	80%	No	Yes	2022
Science mission with full EM-2, A/B to 4,500 km and EDL	4,500	4	80%	Yes	Yes	2026
Science mission with partial EM-2, A/B to 4,500 km, and EDL	4,500	2	80%	Yes	Yes	2029
Science mission with partial EM-2, A/B to 4,500 km, no EDL	4,500	2	80%	Yes	No	2032
Science mission with minimum EM-2 DD, A/B to 4,500 km, and EDL	4,500	1	80%	Yes	Yes	2030
No EM-2 deep dip science, A/B to 4,500 km, and EDL	4,500	0	80%	Yes	Yes	2031
Science mission with full EM-2, maneuver to 1,000 km apoapsis, and EDL	1,000	4	20%	No	Yes	Not enough ΔV for maneuver to 1000 km
Science mission with full EM-2, A/B to 1,000 km and EDL	1,000	4	20%	Yes	Yes	2022
Science mission with partial EM-2, A/B to 1,000 km, and EDL	1,000	2	20%	Yes	Yes	2023
Science mission with partial EM-2, A/B to 1000 km, no EDL	1,000	2	20%	Yes	No	2024
Science mission with minimum EM-2, A/B to 1000 km, and EDL	1,000	1	20%	Yes	Yes	2024
No EM-2 Science mission, A/B to 1,000 km, and EDL	1,000	0	20%	Yes	Yes	2025

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