An Examination of “The Martian” Trajectory

Laura Burke *

NASA Glenn Research Center
Cleveland, OH

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1 Introduction

This analysis was performed to support a request to examine the trajectory of the Hermes vehicle in the novel “The Martian” by Andy Weir[1]. Weir developed his own tool to perform the analysis necessary to provide proper trajectory information for the novel. The Hermes vehicle is the interplanetary spacecraft that shuttles the crew to and from Mars. It is notionally a Nuclear powered vehicle utilizing VASIMR[2] engines for propulsion. The intent of this analysis was the determine whether the trajectory as it was outlined in the novel is consistent with the rules of orbital mechanics.

2 Mission Overview

In the nominal mission scenario, Hermes departs Earth orbit on July 7, 2035 and transports the crew from Earth to Mars where it then aerocaptures into Mars orbit. The specifics of the Mars parking orbit are not provided within the novel. The Mars Descent Vehicle (MDV) delivers the crew to the surface where they will stay for 31 days. After their nominal stay, the crew will use the Mars Ascent Vehicle (MAV) to transport them from Mars surface back to the Hermes in Mars orbit. The Hermes vehicle will then depart Mars and return to Earth. The round trip time of the nominal mission is 396 days.

Weather conditions force the crew to abort to orbit on Sol 6 using the MDV. Following rendezvous the Hermes immediately departs Mars orbit and begins a 236 day return trip to Earth.

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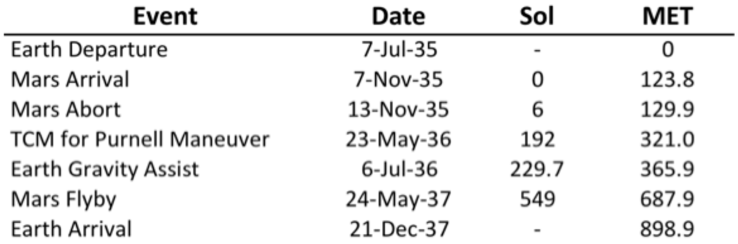
*laura.m.burke@nasa.gov, Mission Architecture and Analysis Branch

On approximately mission day 320, the crew decides to alter the course of the Hermes spacecraft to begin the "Rich Purnell" maneuver. This maneuver is intended to flyby Earth for a gravity assist and return to Mars to retrieve Mark Watney. However, in order to then return back to Earth, the Hermes vehicle cannot capture into Mars orbit so the Hermes will perform a hyperbolic rendezvous with Mark Watney who will have modified the MAV to allow it to launch to Mars escape rather than low Mars orbit. Following the Mars flyby, the crew and Mark Watney will return to Earth 211 days later, 533 days after the planned end of the original abort mission.

2.1 Assumptions

Within "The Martian" Weir has provided information about the Hermes spacecraft as well as its trajectory thoughout the entirety of the mission. The dated of major mission events mentioned are captured in Table 1. Additional details are also discussed in a video of Weir's trajectory analysis[3] which provides more insight as to the particulars of the three different mission scenarios that unfold during the novel.

The trajectory analysis that was completed using the information in the novel assumed the Hermes maintained a constant acceleration of $2\ ^{mm}/_{s^2}$. This clever assumption by the author meant that the mass of the vehicle and the specifics of the propulsion system could be ignored. Although VASIMR is a variable specific impulse thruster and can therefore maintain the thrust to balance the changing mass of the vehicle to provide $2\ ^{mm}/_{s^2}$, an actual mission would take advantage of the increasing thrust-to-weight ratio of the vehicle as propellant is consumed to further increase acceleration thoughout the duration of the mission.



Event	Date	Sol	MET
Earth Departure	7-Jul-35	-	0
Mars Arrival	7-Nov-35	0	123.8
Mars Abort	13-Nov-35	6	129.9
TCM for Purnell Maneuver	23-May-36	192	321.0
Earth Gravity Assist	6-Jul-36	229.7	365.9
Mars Flyby	24-May-37	549	687.9
Earth Arrival	21-Dec-37	-	898.9

Table 1: Mission Events of Final Hermes Trajectory

In order to get an idea of how a "real" Hermes vehicle would perform the VASIMR propulsion system was modeled operating at a constant specific impulse (*isp*) rather than assuming the *isp* varies to produce a constant acceleration. Although optimizing a variable *isp* without maintaining a constant acceleration may improve the overall performance, for simplicity, this analysis fixed the isp at 5000 s. In this manner we can more easily determine the total thrusting time as well as the amount of propellant required to complete each leg of the mission. Previous VASIMR studies[4] of potential Mars mission have used the following performance data:

VASIMR Propulsion System Performance Ranges:

- Power to Propulsion System = 2 MW to 50 MW
- Specific Impulse: 5000 s
- Total System Efficiency: 60 %
- Propellent: Argon

A Hermes vehicle with an inert mass of 110 t was assumed for this comparison trajectory[5]. For the modeling of the nominal mission (the scenario in which the crew stays the full 31 days), the power was optimized in order to minimize the mass of the vehicle at Earth escape (i.e. the beginning of the nominal mission). The arrival date at Mars was also optimized. The original arrival date for the constant acceleration mission from the book (November 8, 2035) resulted in nearly a 30 t increase in mass at Earth escape. All other dates remained unchanged.

In modeling the nominal and early return of the crew contingency trajectories, a closest approach range of 0.8 AU constraint was set in order to ensure that the Hermes spacecraft did not cross within Venus' orbit. This would be a normal mission design constraint in order to reduce radiation exposure as well as much increased thermal loads for the crew and spacecraft. Since the "Rich Purnell" maneuver trajectory in the book is far from nominal or any other contingency scenario that would have been evaluated the closest approach distance of 0.8 AU was relaxed. This may or may not be deemed an acceptable risk.

3 Analysis Tools

3.1 COPERNICUS

COPERNICUS was used to model the constant acceleration as well as the constant specific impulse Hermes trajectories. COPERNICUS is a 3-Degrees of Freedom spacecraft trajectory design and optimization program that was originally developed at the University of Texas with recent developments and maintenance being done by Johnson Space Center[6]. Trajectory models are built as a series of segments propagated in either a point-mass or higher order gravitational field. The segments can be connected and constrained with the addition of linear or non-linear constraints. COPERNICUS has the capability to model both low thrust burns as well as high thrust burns as either impulsively or with finite maneuvers for propulsion systems which can be based on chemical, solar electric, or nuclear powered engines. SPICE files provided by Jet Propulsion Laboratory's NAIF is the basis of coordinate systems and ephemeris data.

4 Constant Acceleration Trajectory

To model a trajectory using a constant acceleration assumption it is not necessary to know specifics of the propulsion system or the vehicle mass at any giving time. It is assumed that the propulsion system will adjust the thrust level to account for the ever-changing mass of the vehicle to provide a constant $2\ {}^{mm}/_{s}$.

Since the departure orbit as well as the method for escaping Earth orbit are not revealed in the novel, this analysis assumed the vehicle started at escape from Earth with a $C3 = 2^{km^s}/_{s^s}$ (which is consistent with performing an outbound lunar flyby). Similarly, since the parking orbit at Mars was unknown, all Mars departures left with an escape energy of $C3 = 0^{km^s}/_{s^s}$. In order to achieve these departure specifications some additional propulsive maneuvers around Earth and Mars are required but have not been modeled in this study.

Since the Hermes vehicle either aerocaptures or aerobrakes at Mars the Hermes vehicle can approach on a hyperbolic trajectory at a relatively low altitude necessary to produce the Lift-to-Drag ratios required of these maneuvers. The nominal scenario generated for this study assumed the Hermes approached Mars with a hyperbolic excess velocity, V_{inf}, of 5.36 ${}^{km}/_{s}$ at an altitude of 100 km.

If the arrival date at Mars is added into the optimization for the nominal trajectory, the Hermes arrives at Mars approximately 27 days earlier than the date stated in the novel. When calculating this trajectory the author adjusted the nominal arrival date at Mars to ensure that the 31 day stay included Thanksgiving. Forcing the arrival date to occur later than the optimal arrival date resulted in approximately 60 more days of thrusting and 60 additional days worth of required propellent.

During the abort scenario, although the Earth arrival/resupply flyby occur earlier than the nominal Earth arrival date, the time the Hermes vehicle has to transit from Mars back to Earth remains nearly the same given that a shorter time was spent at Mars. When the abort occurs on Sol 6 the Hermes spacecraft is actually able to depart Mars closer to the optimal departure date (mid-October 2035) for this opportunity. This results in a slightly better performing Earth return phase of the mission than the nominal trajectory had planned for. This also means that there is more than enough propellant onboard the baseline vehicle to support the return to Earth abort scenario.

It is unknown what orbit the Hermes vehicle would have captured into when it returns to Earth so this analysis made the assumption that the entry velocity at Earth should not exceed 11.5 $^{km}/_{s}$. This limit is consistent with what is usually assumed when a human crewed capsule performs a direct entry return to Earth. Similarly, it is unknown if there were any relative velocity constraints for re-supply flyby during the "Rich Purnell" maneuver. For this analysis the Earth arrival V_{inf} was constrained to be less than 6 $^{km}/_{s}$.

There are some details in the novel regarding the Mars flyby in which the Hermes will attempt to perform a hyperbolic rendezvous with Mark Watney. It can be inferred from the descriptions in the novel that Mark Watney is near the edge of Mars atmosphere, an altitude near 250 km, and it is stated that the MAV must be modified to be able to match the 5.8 $^{km}/_{s}$ relative velocity of the Hermes during the flyby. Those values were used as constraints for the Mars rescue flyby for the "Rich Purnell" phase of the mission. Giving these constraints and the fixed event dates, the Purnell maneuver requires slightly less thrusting time than the original non-optimized nominal mission, therefore still within the original propellant budget the Hermes would have carried to perform its nominal mission.

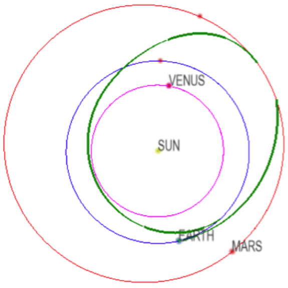


Figure 1: Nominal Hermes Trajectory

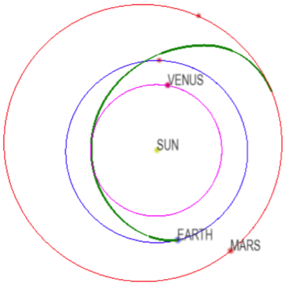


Figure 2: Abort Trajectory Following Sol 6 Abort

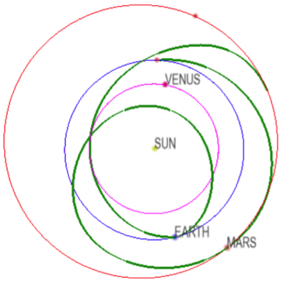
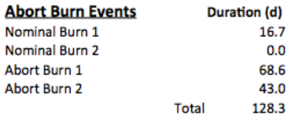


Figure 3: Rich Purnell Hermes Trajectory

Additional details regarding the burn times for the nominal, contingency, and "Rich Purnell" maneuver flight plans are provided in the tables below:

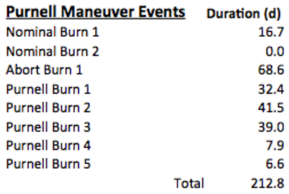
Nominal Burn Events		Duration (d)
Burn 1		16.7
Burn 2		0.0
Burn 3		85.4
Burn 4		120.1
	Total	222.3

Figure 4: Nominal Burn Durations



Abort Burn Events		Duration (d)
Nominal Burn 1		16.7
Nominal Burn 2		0.0
Abort Burn 1		68.6
Abort Burn 2		43.0
	Total	128.3

Figure 5: Abort Burn Durations



Purnell Maneuver Events		Duration (d)
Nominal Burn 1		16.7
Nominal Burn 2		0.0
Abort Burn 1		68.6
Purnell Burn 1		32.4
Purnell Burn 2		41.5
Purnell Burn 3		39.0
Purnell Burn 4		7.9
Purnell Burn 5		6.6
	Total	212.8

Figure 6: Rich Purnell Burn Durations

5 Constant Specific Impulse Trajectory

In addition to modeling the trajectory with a content acceleration propulsion system, the trajectory was also modeled with a VASMIR propulsion system providing a constant specific impulse of 5000 s and pushing a Hermes vehicle with an inert mass of 110 t. Modeling the trajectory this way, the optimizer is able to take advantage of the ever increasing acceleration of the vehicle due to the mass lost from the consumption of propellent. It is also easier to understand how propellent is being consumed since it will have a constant mass flow rate.

Results presented in this section will be for both the original Mars arrival date from the novel as well as a variable arrival date determined through the optimization process. The optimal arrival date in this case ended up being 24 days prior to the date the crew arrives at Mars in the novel. Allowing the arrival date to occur earlier reduces the total amount of propellent necessary for the nominal mission, resulting in a lower mass at Earth escape as well as resulting in less propellent being consumed during the abort scenario and the "Rich Purnell" maneuver scenario. Whether the decrease in propellent mass for the abort trajectory and "Rich Purnell" trajectory is due to the overall lower escape mass of the vehicle or due to better planetary alignment during the interplanetary transit is unknown at this point. Additionally, the earlier Mars arrival date also allows the propulsion system to accomplish the mission with a lower power level than if the original arrival date is maintained: 15.45 MW instead of 17.37 MW.

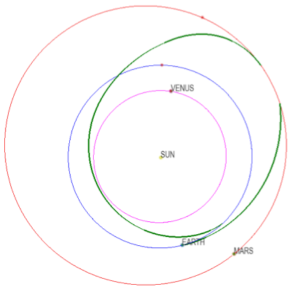


Figure 7: Nominal Hermes Trajectory - Fixed Mars Arrival Date

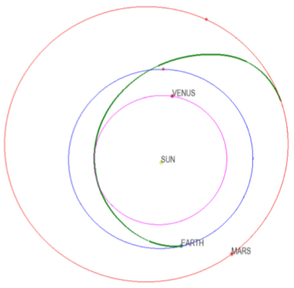


Figure 8: Abort Trajectory Following Sol 6 Abort

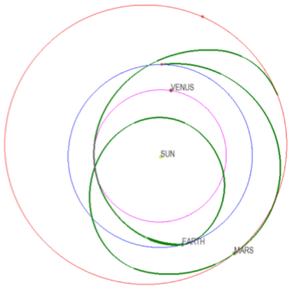


Figure 9: Rich Purnell Hermes Trajectory

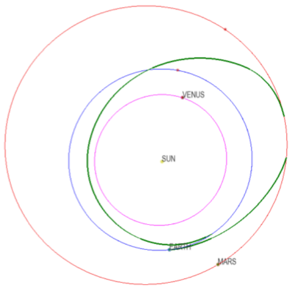


Figure 10: Nominal Hermes Trajectory - Optimal Mars Arrival Date

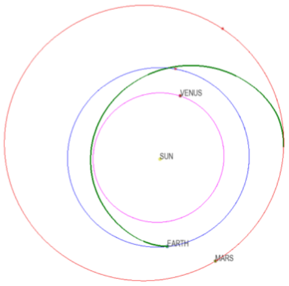


Figure 11: Abort Trajectory Following Sol 6 Abort

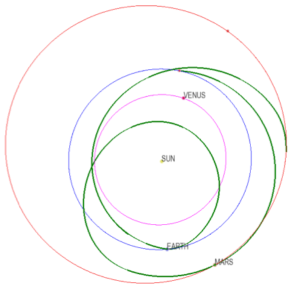
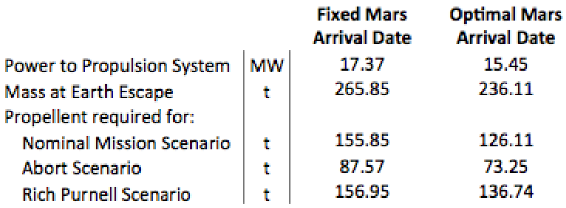


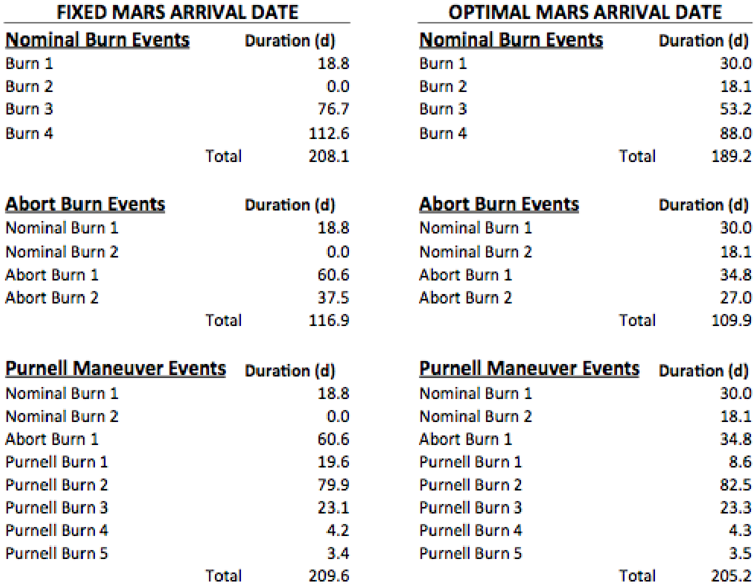
Figure 12: Rich Purnell Hermes Trajectory



		Fixed Mars Arrival Date	Optimal Mars Arrival Date
Power to Propulsion System	MW	17.37	15.45
Mass at Earth Escape	t	265.85	236.11
Propellent required for:			
Nominal Mission Scenario	t	155.85	126.11
Abort Scenario	t	87.57	73.25
Rich Purnell Scenario	t	156.95	136.74

Figure 13: Escape Mass and Propellent Requirements for Mission Scenarios

Additional details regarding the burn times for the nominal, contingency, and "Rich Purnell" maneuver flight plans are provided in the tables below:



FIXED MARS ARRIVAL DATE

Nominal Burn Events		Duration (d)
Burn 1		18.8
Burn 2		0.0
Burn 3		76.7
Burn 4		112.6
	Total	208.1

Abort Burn Events		Duration (d)
Nominal Burn 1		18.8
Nominal Burn 2		0.0
Abort Burn 1		60.6
Abort Burn 2		37.5
	Total	116.9

Purnell Maneuver Events		Duration (d)
Nominal Burn 1		18.8
Nominal Burn 2		0.0
Abort Burn 1		60.6
Purnell Burn 1		19.6
Purnell Burn 2		79.9
Purnell Burn 3		23.1
Purnell Burn 4		4.2
Purnell Burn 5		3.4
	Total	209.6

OPTIMAL MARS ARRIVAL DATE

Nominal Burn Events		Duration (d)
Burn 1		30.0
Burn 2		18.1
Burn 3		53.2
Burn 4		88.0
	Total	189.2

Abort Burn Events		Duration (d)
Nominal Burn 1		30.0
Nominal Burn 2		18.1
Abort Burn 1		34.8
Abort Burn 2		27.0
	Total	109.9

Purnell Maneuver Events		Duration (d)
Nominal Burn 1		30.0
Nominal Burn 2		18.1
Abort Burn 1		34.8
Purnell Burn 1		8.6
Purnell Burn 2		82.5
Purnell Burn 3		23.3
Purnell Burn 4		4.3
Purnell Burn 5		3.5
	Total	205.2

Figure 14: Comparison of the Burn Event Durations during each Mission Scenario

By forcing the nominal trajectory to perform a longer outbound transit in order to align the surface stay with Thanksgiving, the nominal mission required an additional 30 t of propellent over the minimum required amount when the Mars arrival date is allowed to occur earlier. However, due to this imposed arrival constraint, the Hermes had nearly sufficient propellent remaining to perform the "Rich Purnell" maneuver. The Hermes would more than likely have sufficient propellent reserves onboard to make up the 1.1 t difference.

6 Conclusions

This analysis confirms that the nominal trajectory as well as both contingency trajectories within "The Martian" are consistent with the laws of physics as they were modeled and portrayed in the book. Additionally, by modeling the original non-optimized trajectory using VASIMR performance characteristics pushing a 110 t Hermes vehicle, it has been shown that all phases of the trajectory in this novel converge and that the resulting amount of required propellant is within a believable range for this class of vehicle. Also, since the nominal trajectory was intentionally modified to lengthen the outbound transit time (to be on the surface over Thanksgiving) an additional 30 t of propellent was present that would have not been otherwise. This additional propellent (along with some of the propellent margin that would more than likely be present) gives the Hermes just enough propellent to perform the "Rich Purnell" maneuver to rescue Mark Watney. However, since "Rich Purnell" maneuver would result in the Hermes transiting well within the orbit of Venus, exposing both the crew and spacecraft to large levels of radiation and high temperatures, this rescue scenario may not be a possibility depending on physical limits of the crew and spacecraft.

However, as VASIMR has yet to be demonstrated in space, it is unknown as to the viability of this vehicle itself. It is becoming more evident that mission architectures which employ low-thrust technology paired with a substantial power source[7],[8],[9] can perform Mars mission much more efficiently than all-chemical architectures. Nuclear Electric Propulsion (NEP) is particular well suited to short-duration Mars mission due to the inclusion of a constant power source. It would be of interest in the future to compare the VASIMR trajectories in this study with a similarly sized Bimodal Nuclear Thermal Electric Propulsion (BNTEP) vehicle[9] or potential an NEP-Chemical vehicle.

7 Acknowledgements

Thank you to Michael Greshko, journalist with Inside Science News Service at the American Institute of Physics, for allowing me to dive deeper into a novel that I already loved and Andy Weir for writing a novel which will inspire people to take a closer look at Mars and the science and technology that goes into supporting Mars exploration missions. Additionally, thank you to Melissa McGuire (NASA, GRC) for always keeping me busy with the most interesting projects.

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