

Comparative Performance of Entry Simulations using Guided Human-Scale Landers at Mars

Evan Roelke¹ and Alejandro R. Pensado²

Analytical Mechanics Associates, Hampton, VA, 23666, USA

Breanna J. Johnson³ and Daniel A. Matz⁴

NASA Johnson Space Center, Houston, TX, 77058, USA

Rafael A. Lugo⁵ and Soumyo Dutta⁶

NASA Langley Research Center, Hampton, VA, 23681, USA

There has been ongoing interest in human exploration of Mars since the 1970s. Most studies to date have investigated moderate lift-to-drag ratio vehicles to investigate this problem. This paper considers the development and cross-simulation comparison of a slender-bodied, moderate lift-to-drag human-scale lander vehicle for Mars. The vehicle employs the Fully Numerical Predictor-corrector Entry Guidance to target a powered descent state, subsequently leveraging Fractional Polynomial Powered Descent Guidance laws to reach the desired touchdown target. Differences in simulation environment as well as nominal trajectory results are shared.

I. Introduction

Human-scale Mars missions have been studied for the past several decades, starting as early as during the Apollo program [1]. Robotic exploration of Mars has been a fruitful effort, with several successful missions since the 1970s starting with the Viking program, and more recently the Mars2020 Rover [2, 3]. While successful, the latest robotic missions to Mars have tested the limits on viable entry, descent, and landing (EDL) configurations given current technological capabilities [2]. A human-scale Mars entry vehicle will thus require an innovation in both vehicle configuration and EDL concept of operations.

There have been numerous architecture studies regarding human-scale vehicles in the past decade. Several studies investigated leveraging the heritage of blunt body aeroshells with low lift-to-drag (L/D) ratios for this purpose [4, 5]. Mid-L/D vehicles have been considered for decades, including a 1990s ellipsled concept, first proposed for delivering a habitation module to Mars and further considered for additional human Mars studies [6]. More recently, deployable decelerators such as the Hypersonic Inflatable Aerodynamic Decelerator (HIAD) and Adaptable Deployable Entry

¹ Aerospace Engineer, Atmospheric Flight & Entry Systems Branch, AIAA Member.

² Aerospace Engineer, Atmospheric Flight & Entry Systems Branch, AIAA Senior Member.

³ Aerospace Engineer, Flight Mechanics and Trajectory Design Branch, AIAA Member.

⁴ Flight Dynamics Modeling Technical Discipline Lead, Flight Mechanics and Trajectory Design Branch, AIAA Senior Member.

⁵ Aerospace Engineer, Atmospheric Flight & Entry Systems Branch, AIAA Senior Member.

⁶ Aerospace Engineer, Atmospheric Flight & Entry Systems Branch, AIAA Associate Fellow.

Placement Technology (ADEPT) were investigated [7]. Subsequently, the Entry, Descent, and Landing Architecture Study (EDLAS) performed a technology assessment of four unique entry configurations, considering both low- and mid-L/D rigid body concepts [5, 8, 9]. Ref. [8] considers a vehicle design based off the Co-Optimization Bluntbody Re-entry Analysis (COBRA) shape optimization process developed at NASA Ames named the Cobra Mid-L/D Rigid Vehicle (CobraMRV) vehicle, a variation of which is used in this work. This study notes that mid-L/D vehicles offer advantages over low-L/D vehicles such as providing potential constraint mitigation in addition to extended downrange and crossrange capabilities.

This paper considers the development of a slender-bodied, human-scale lander at Mars using two independent simulations: The Program to Optimize Simulated Trajectory II (POST2) [10, 11] and Genesis [12]. The two simulations use identical vehicle, mission, and planet properties, conceptualizing a scaled-up version of the CobraMRV vehicle to match the payload capacity of more recent, human-lander scale designs, which are referenced from the public domain of commercial companies. Differences in the simulations' performance are highlighted and explored. One primary goal of using two different simulations is to provide an initial level of independent verification and validation (IV&V) between a flight-validated, industry-standard simulation tool (POST2) and a more recent simulation tool developed with support from the NASA Engineering Safety Center (NESC) that takes advantage of more modern programming standards and environments (Genesis).

II. Modeling and Simulation

This paper focuses on the performance analysis of a mid-L/D, slender-bodied entry vehicle at Mars scaled up from the CobraMRV concept described in Ref. [8]. The traditional CobraMRV concept was intended to land on its side, but this paper considers an alternative vertical landing approach, like previous NASA efforts exploring vertical lander technologies with its industry partners [13, 14, 15, 16]. Two guidance algorithms are used to steer the vehicle through the upper atmosphere and perform powered descent. This section covers the mission design, vehicle design, guidance algorithms, and simulation environments used to assess performance.

A. Vehicle and Mission Design

The entry vehicle conceptualized for this analysis is a scaled-up version of the CobraMRV concept from Ref. [8]. A depiction of the vehicle is presented in Figure 1 and the vehicle properties are summarized in Table 1. The lander's diameter is scaled to match the planned diameter of the Space Launch Vehicle (SLS) payload faring. This results in a vehicle of similar size to a commercial vertical lander [13]. The entry mass and vehicle thrust were chosen in a similar manner. The vehicle aerodynamics match those of the CobraMRV vehicle based on the assumption that scaling the vehicle appropriately would have a negligible impact on these properties. The concept of operations (CONOPS) is summarized in Figure 2. The vehicle is initialized at atmospheric interface with the state vector described by Table 2.

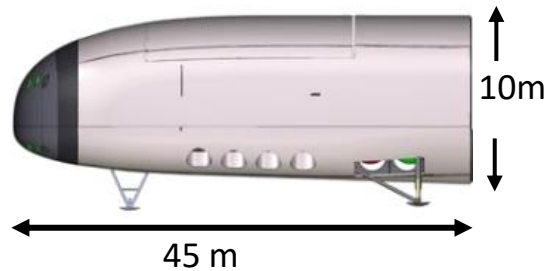


Figure 1: Scaled-up CobraMRV concept

Table 1: Vehicle and Mission properties

Parameter	Value
Configuration	Scaled CobraMRV
Diameter	10 m
Vehicle Length	45 m
Entry Mass	1,450 t
Thrust	3.75 million N
Aerodynamics	CobraMRV [8]

The vehicle flies at a fixed angle of attack of 55° to produce sufficient lift force to provide maneuverability at upper altitudes. Due to the high mass and thus high ballistic coefficient combined with the low density of the Martian atmosphere, it takes a considerable amount of time for aerodynamic forces to dominate those from gravity.

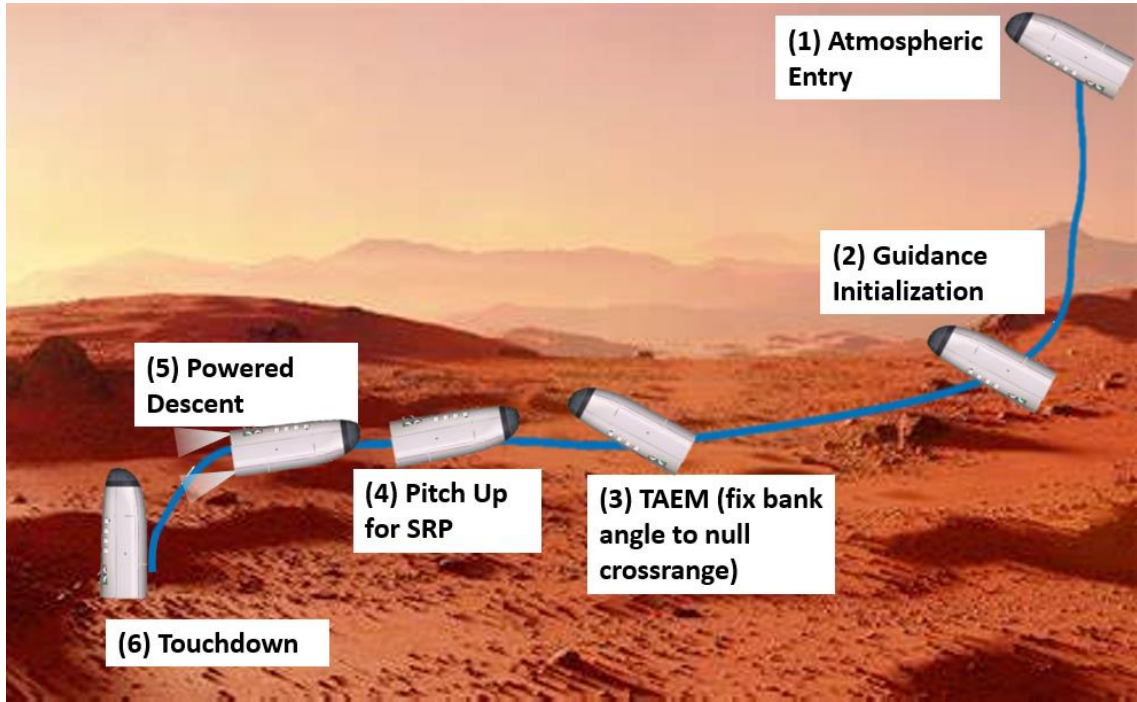


Figure 2: Concept of operations for human-scale Mars entry trajectory using scaled-up CobraMRV design.

Guidance is activated when the vehicle's sensed acceleration exceeds a predefined threshold to ensure vehicle controllability. Once the planet-relative velocity drops below a given threshold the vehicle executes a Terminal Area Energy Management (TAEM) maneuver for heading alignment. This sets the bank angle to a fixed value to zero out any remaining crossrange error. The spacecraft subsequently performs a pitch-over maneuver to align the engines along the velocity vector (flying at an angle of attack of 180°) before initiating Supersonic Retropropulsion (SRP) for the powered descent phase until touchdown.

Table 2: Nominal initial conditions

Parameter	Value
Altitude	122 km
Velocity	7500 m/s
Flight path angle	-14.3385°
Latitude	-17.1673°
Longitude	0°
Azimuth	0°
Julian date	2458608.8654850
Target Latitude	0°
Target Longitude	0°

B. Simulation Environments

Two NASA flight mechanics simulation tools are used for performance analysis. The comparison of the two simulations is part of a larger effort to help demonstrate the capability of multiple NASA simulation tools to be quickly applied to flight mechanics problems and compare results [17]. In addition, the use of two simulations provides opportunities for independent verification and validation (IV&V) of the tools. Both simulations use the same vehicle mass properties, aerodynamics, guidance algorithms, and planet properties, which are defined in Table 3.

Table 3: Planet and environment properties

Parameter	Value
Planet	Mars
Equatorial Radius	3396190 m
Polar Radius	3376200 m
Standard Gravitational Parameter	4.2828376383e13 m ³ /s ²
Gravity	MGS85F2 85x85 Mars Gravity Model
Rotation Rate	7.088218e-5 rad/s
Atmosphere	MarsGram 2010

1. Program to Optimize Simulated Trajectories II (POST2)

POST2 is a flight-validated flight mechanics simulation tool that can provide multi-body 3- and 6-degree-of-freedom spacecraft modeling with both exo- and endo-atmospheric integration capabilities [10, 11]. The POST2 source code was originally written in FORTRAN to support NASA Space Transportation Systems (STS) in the 1970s but has since been re-written in C, which subsequently enabled vast updates and modularization to support multiple flight programs such as all NASA Mars atmospheric EDL systems over the past two decades [18, 19, 20, 21, 22, 23], the NASA Space Launch System (SLS) [24], the NASA Commercial Crew Program (CCP), and the NASA Human Landing System (HLS) [25], among others.

2. Genesis

The second tool, Genesis, is a relatively new flight mechanics simulation tool developed to be the successor to the Flight Analysis and Simulation Tool (FAST). Genesis is a generic, multi-vehicle, variable-degree-of-freedom flight mechanics simulation for trajectory design [26]. It enables rapid mission design and is capable of modeling ascent, aerocapture, entry, descent, and landing trajectories around a single planetary body. It is designed to be flexible, supporting low- to high-fidelity models, and easily reconfigured for new vehicles. Genesis provides generic models for atmospheric properties, winds, aerodynamics, and propulsion. It can easily be extended with new environment, vehicle, or flight software models. Genesis can be used for a wide variety of analyses, ranging from optimizing a single trajectory to running a large Monte Carlo analysis in a High-Performance Computing (HPC) environment. It consolidates and replaces a suite of NASA legacy flight mechanics simulations. It is implemented in the Julia programming language [27].

C. Guidance Algorithms

1. Entry Guidance

The vehicle is steered through the atmosphere starting from the minimum sensed acceleration threshold until TAEM using bank angle modulation. Bank angle modulation, depicted using a standard blunt-bodied aeroshell in Figure 3, rotates a vehicle about its velocity vector, which thus rotates the lift vector out of plane, reducing the vertical lift force and producing a side force. By modulating the bank angle (and thus the vertical lift component), the vehicle can control its downrange to attain desired entry targeting conditions.

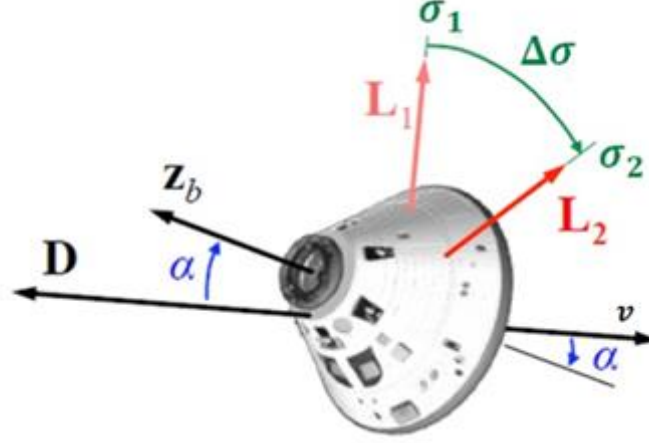


Figure 3: Example of bank angle modulation for EDL

The Fully Numerical Predictor-corrector Entry Guidance (FNPEG) is incorporated into both simulations to produce bank angle commands throughout the entry guidance phase [28]. This guidance algorithm employs a numerical predictor-corrector scheme to solve for the commanded bank angle at each instant in time that satisfies vehicle constraints (such as peak heating or peak acceleration limits), vehicle boundary conditions (such as minimum and maximum bank angles and bank angle rate/acceleration limits) and targeting conditions. The algorithm is composed of a longitudinal and a lateral solution, where the former numerically integrates the vehicle trajectory from its current state to the termination of the entry phase and the latter determines when to perform bank reversal using a velocity-dependent deadband on the heading error. A Gauss-Newton method is employed to update the desired bank angle command to minimize the range to target based on the user-specified entry phase termination energy condition. A lateral logic step is then invoked to perform bank reversals to reduce heading error. The FNPEG guidance uses an internal polynomial curve fit of the atmospheric density. The POST2 FNPEG routine implements a nominal aerodynamic coefficient table look up routine, whereas the Genesis simulation implements a 2nd order polynomial curve fit of these coefficients. It should be noted that a primary goal of this work is to compare guidance algorithm performance across multiple simulations; this resulted in minor discrepancies in guidance inputs such as in this case, which is likely to cause some differences in guidance outputs.

Finally, the FNPEG guidance properties used in this analysis are summarized in Table 4. The termination of the entry phase is set slightly before the target latitude/longitude to account for the powered descent phase.

Table 4: FNPEG GN&C properties.

Parameter	Value
Target Altitude	4090 m
Target Velocity	600 m/s
Target Latitude	-0.16°
Target Longitude	0.03°
Aerothermal/Sensed Deceleration Constraints	N/A

2. Powered Descent

The powered descent phase of EDL consists of the vehicle generating a thrust force against its velocity vector with the goal of nulling out both horizontal and vertical components of velocity. The simplest form of this family of maneuvers is called the gravity turn, in which the vehicle produces thrust exactly opposite the velocity vector at each moment in time. The timing of powered descent initiation (PDI) thus depends on the vehicle's thrust capability, assuming a constant thrust profile. More advanced forms of powered descent guidance algorithms exist, such as the Apollo powered descent guidance (A²PDG) [29] and E-guidance [30] as well as convex optimization powered descent routines [31]. The former two guidance schemes are a subset of a form of fractional polynomial powered descent guidance laws (FP²DG) [32], which generates acceleration commands according to:

$$\mathbf{a}_T = \gamma \left[\frac{k_r}{2(\gamma+2)} - 1 \right] \mathbf{a}_{T_f} + \left[\frac{\gamma k_r}{2(\gamma+2)} - \gamma - 1 \right] \mathbf{g} + \frac{\gamma-1}{t_{go}} \left(1 - \frac{k_r}{\gamma+2} \right) (\mathbf{v}_f - \mathbf{v}(t)) + \frac{k_r}{t_{go}^2} (\mathbf{r}_f - \mathbf{r} - \mathbf{v}(t)t_{go}) \quad (1)$$

Where $\mathbf{a}_T$ is the commanded acceleration vector, γ and k_r are parametrization constants to shape the desired polynomial solution, $\mathbf{r}_f$, $\mathbf{v}_f$, and $\mathbf{a}_f$ are the target position, velocity, and acceleration vectors in the guidance coordinate system, $\mathbf{g}$ is the gravitational acceleration vector, t_{go} is the desired powered descent phase time, and $\mathbf{r}$ and $\mathbf{v}$ are the vehicle's current position and velocity vectors, also expressed in the guidance coordinate system. The parametrization constants, γ and k_r , generate a family of polynomial curves for acceleration (and therefore throttle) commands as depicted in Figure 4. Note that FP²DG has also been investigated in previous 6-DoF CobaMRV studies [31, 32].

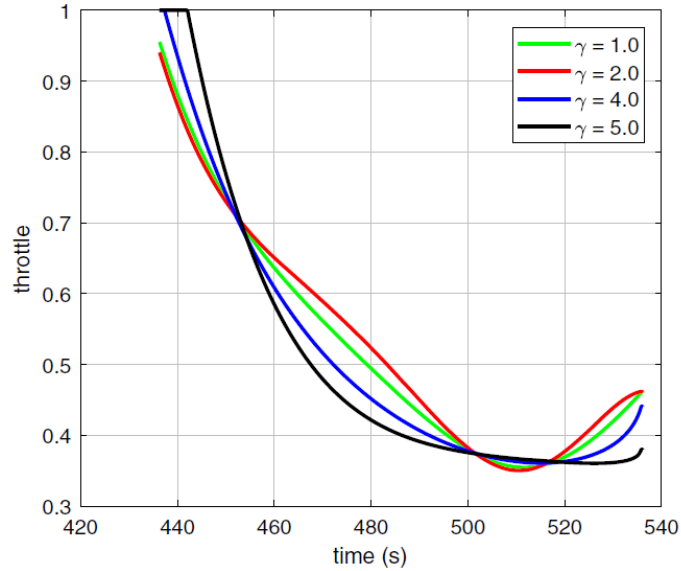


Figure 4: Engine throttle polynomial families using FP²DG with $k_r = 15$ [28]

A flat planet coordinate system is chosen for convenience to express variables in guidance coordinates because the origin of the flat planet frame can be selected as the target position, simplifying guidance inputs. The polynomial acceleration command is obtained at each time step by evaluating Equation 1 at each time step for a decreasing t_{go} . The output acceleration command is then converted to a thrust command in body-frame coordinates under the assumption that the vehicle could gimbal its engines appropriately. Table 5 shows the settings selected for FP²DG in this effort.

Table 5: Fractional polynomial guidance properties

Parameter	Value
γ	12
k_r	1
$\mathbf{a}_F$	[0, 0, 0] m/s ²
$\mathbf{v}_F$	[0, 0, 1.0] m/s
$\mathbf{r}_F$	[0, 0, 0] m/s
t_{go}	38 s

III. Results

This section details the comparative performance assessment of the EDL scenario using both POST2 and Genesis. Section III.D compares nominal trajectories while Section III.E showcases initial Monte Carlo results.

A. Simulation Environment Comparison

This section presents the comparisons between simulation environments in Genesis and POST2. Both simulations used MarsGRAM 2010 for this analysis, with matching planet and input parameters previously defined in Table 3. Figure 5 depicts the percent difference in atmospheric density between POST2 and Genesis as a function of altitude, which is computed by performing a logarithmic interpolation of POST2 density points at the Genesis trajectory altitudes. A dashed line is provided to signify the altitude at which entry guidance is activated.

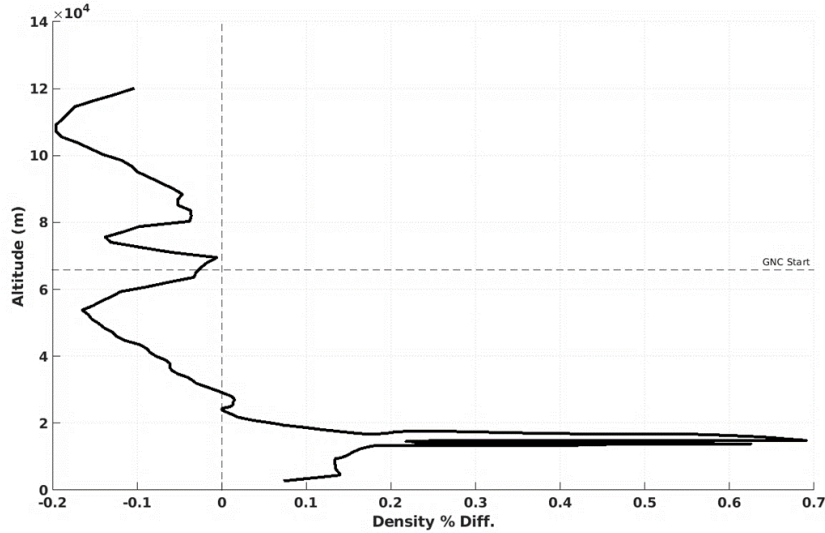


Figure 5: Percent difference in MarsGRAM 2010 density between POST2 and Genesis

Percent differences are all less than 1% in magnitude across the entire altitude span, suggesting good agreement between inputs and outputs. Additional atmospheric model output comparisons are shown in Figure 6, which shows the vehicle speed of sound and Mach number as functions of time.

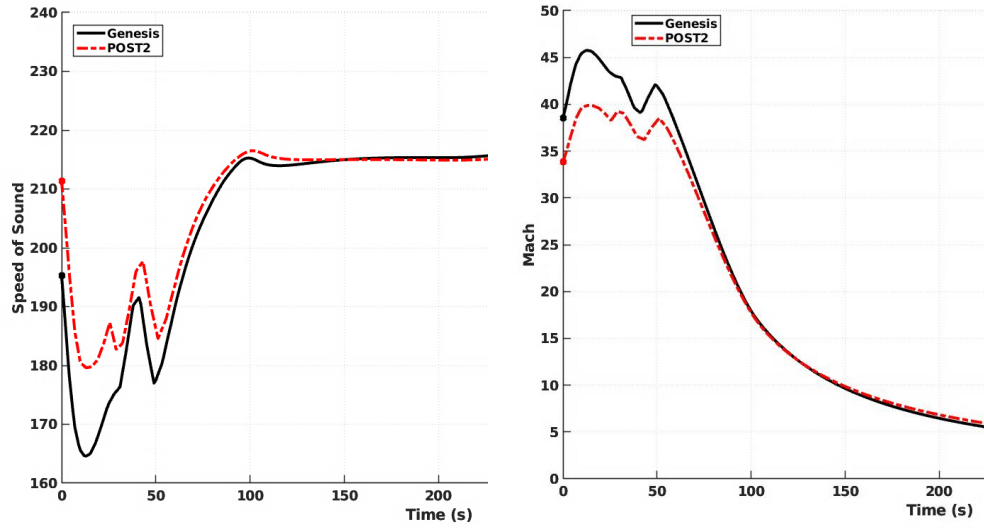


Figure 6: Speed of Sound and Mach vs. Time

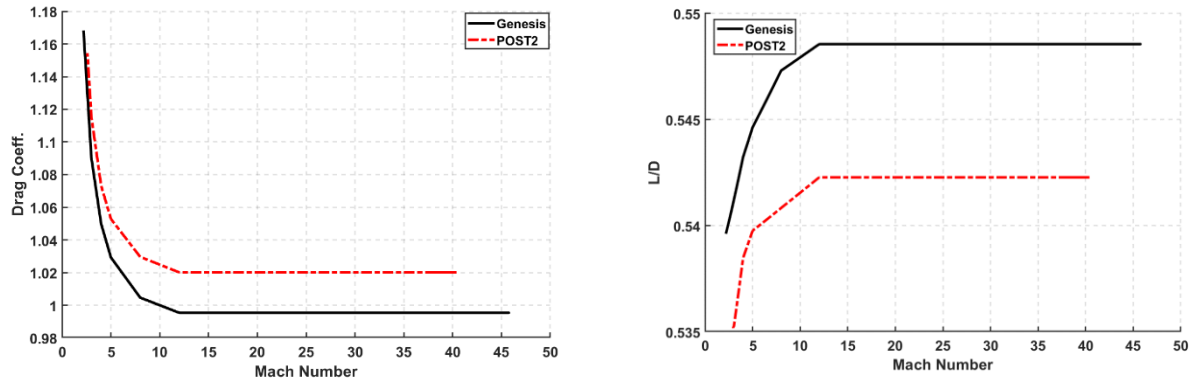


Figure 7: Drag coefficient and lift-to-drag ratio vs. Mach.

It is immediately apparent that there is a discrepancy in the speed of sound at the start of the simulation, which subsequently leads to a difference in Mach number between the two simulations. There is an ongoing effort to understand this difference; possible sources include a known MarsGRAM 2010 speed of sound calculation bug or Knudsen number computation differences. As shown in Figure 7, which presents the drag coefficient and L/D as functions of Mach number between the two simulations, the difference in Mach number results in minor discrepancies in vehicle aerodynamics (and thus also ballistic coefficient). The difference is relatively small but may result in minor differences in the overall trajectory and guidance commands. However, the percent difference in vehicle lift-to-drag is about 1% at the start of the simulation and decreases as the vehicle decelerates.

B. Entry Phase Results

This section covers trajectory simulation comparisons for the entry phase using the FNPEG conditions outlined in Table 4. As such, Figure 8 presents nominal trajectory comparisons up to the termination of the entry phase.

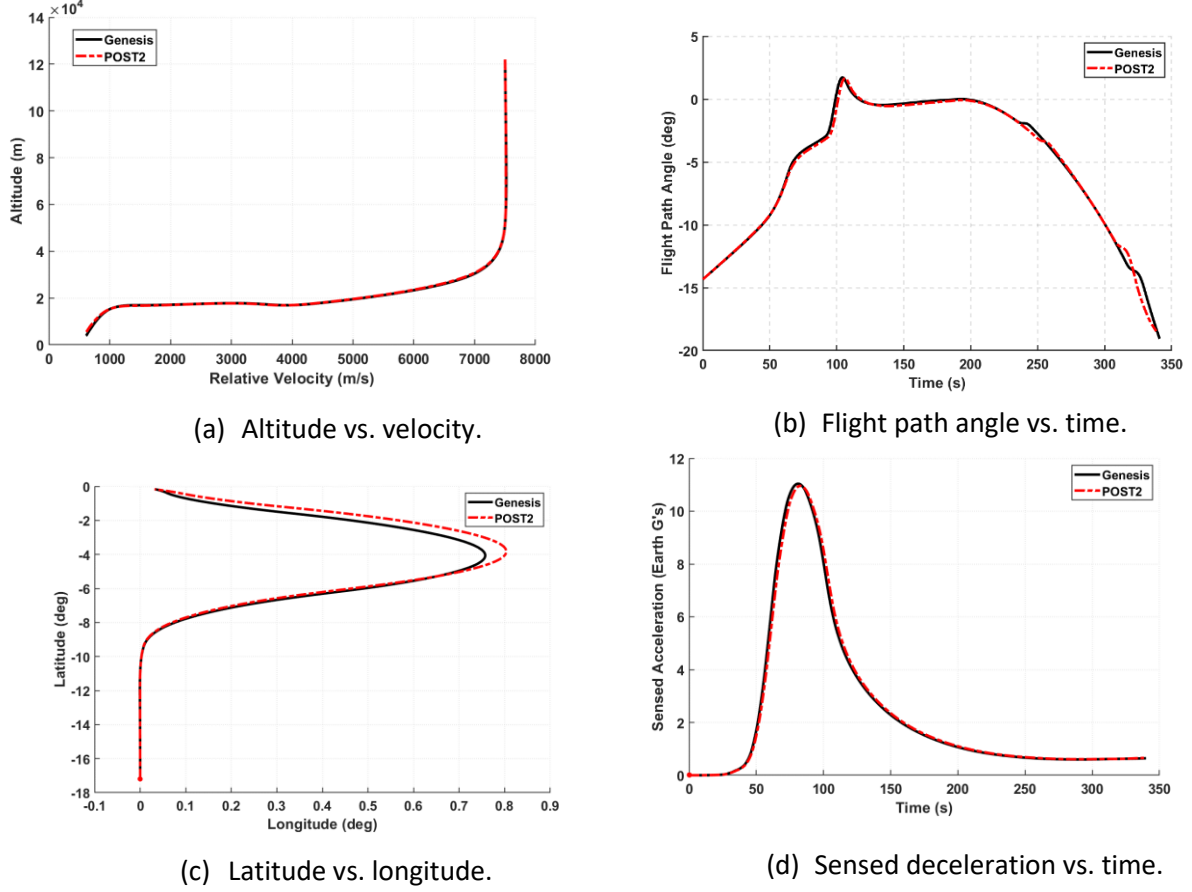
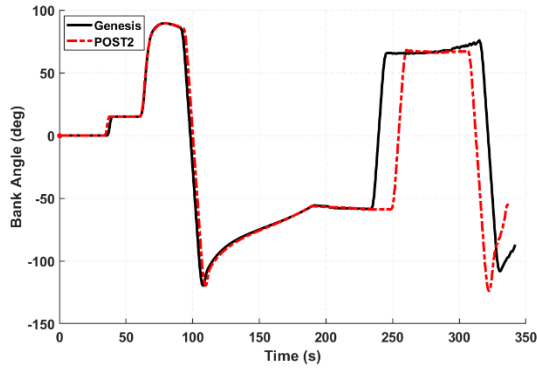
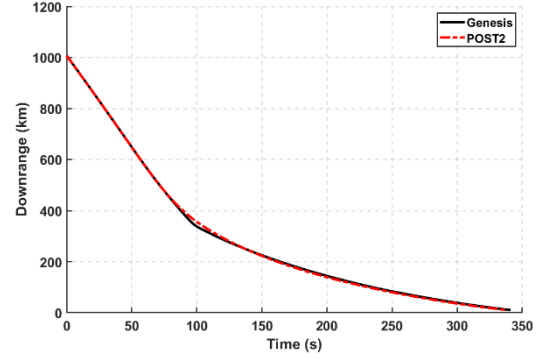


Figure 8: Nominal trajectory comparison

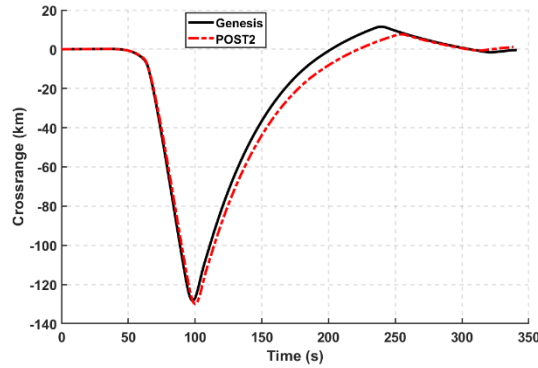
The top-left figure presents the trajectory in altitude-velocity space, the top-right shows flight path angle vs. time, the bottom-left depicts the latitude vs. longitude vehicle groundtrack, and the bottom-right showcases the vehicle sensed acceleration vs. time. There is overall agreement between trajectories; minor differences may be attributed to slight discrepancies in vehicle aerodynamics shown in Section III.A. Similarly, Figure 9 presents time histories of guidance-related parameters due to the outputs of the FNPEG routine. The top-left plot shows the bank angle vs. time, while the top-right and bottom figures show the downrange and crossrange vs. time, respectively. Even though the trajectories and bank angle profile deviate slightly after 200 seconds of flight, the vehicles are both able to reach the target FNPEG termination conditions, driving downrange and crossrange close to zero in both simulations. This agreement is an indicator that the guidance algorithms are performing nearly identically even though the codebase may differ slightly between the two simulations. However, the authors would again like to point out that this holistic trajectory data comparison could be improved by a shared guidance algorithm repository and associated unit tests.



(a) Bank angle vs. time.



(b) Downrange error vs. time.

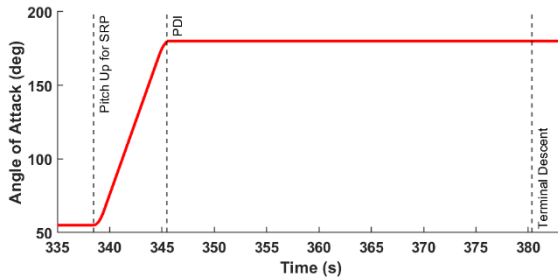


(c) Crossrange error vs. time.

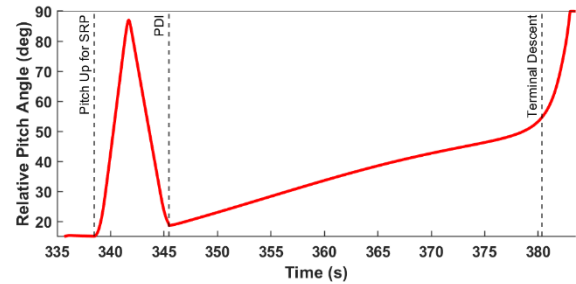
Figure 9: FNPEG guidance comparisons

C. Powered Descent Results

This section outlines initial powered descent performance results. Powered descent is initiated following FNPEG termination and employs Fractional Polynomial Powered Descent Guidance (FP²DG), as described in Section II.C.2. Due to time constraints, the Genesis simulation did not model a pitch-up maneuver for this study. However, the POST2 simulation modeled the pitch-up maneuver over a short time span, as shown in Figure 10, which displays the POST2 vehicle orientation during the pitch up and powered descent phases. Figure 10a shows the angle of attack as a function of time and Figure 10b displays the body-relative pitch angle.



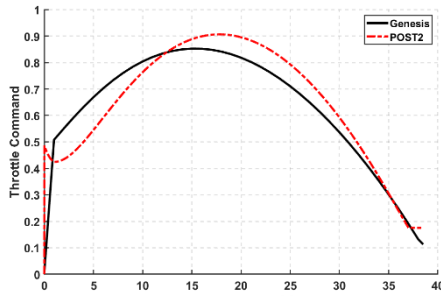
(a) Angle of attack vs. time



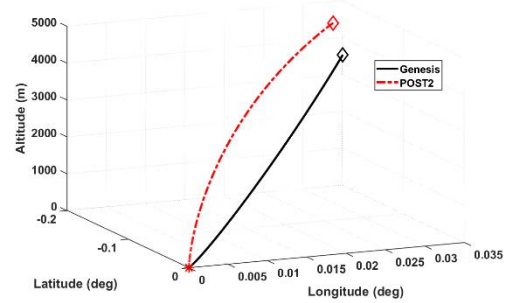
(b) Relative pitch angle vs. time

Figure 10: Vehicle orientation during powered descent

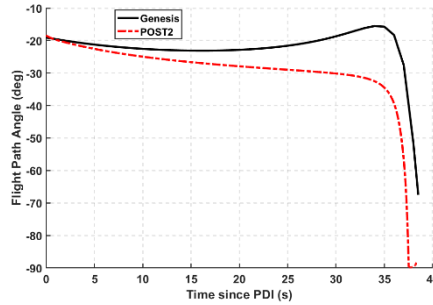
During the pitch-up maneuver prior to powered descent, the vehicle aligns its engines with the velocity vector to land vertically. This is modeled as a linear increase in angle of attack over a 7 second period, as shown in Figure 10a. The engines are engaged and throttled to 30% during this time under the assumption that gimbaling the thrust would increase the speed of the pitch-up maneuver. Figure 10b shows the vehicle passing through the pitch angle singularity of 90° , at which point the angle is measured from south instead of north. This causes the relative pitch angle to decrease again leading up to powered descent initialization (PDI), coinciding with the increase in angle of attack to 180° , signifying that the vehicle is flying with its engines into the wind and is close to horizontal relative to the surface once more. Following PDI the relative pitch angle is shown to increase up to the desired landing orientation of 90° , indicating a vertical touchdown as desired. The Genesis simulation did not model a pitch-over maneuver; however, results are still compared between powered descent initialization (PDI) and touchdown. The associated FP^2DG throttle command comparison is shown in Figure 11a, while the descent trajectory comparisons are shown in Figure 11b and 11c. The throttle command is dictated by the magnitude of the guidance output acceleration command, while the acceleration vector itself is rotated from the guidance coordinate system (flat planet coordinates, in this case) to body-relative coordinates.



(b) Throttle command vs. time.



(a) Altitude vs. groundtrack.



(c) Flight path angle vs. time since PDI.

Figure 11: Powered descent guidance performance

Differences in the descent trajectory shown in Figure 11b can be explained due to slight differences in how the simulation models flight between the entry phase termination and PDI. For example, the Genesis trajectory used the Universal Powered Guidance (UPG) Boltza soft landing routine to predict when to begin PDI [33, 34]. While initial positions differ slightly, the FP^2DG guidance commands are able to deliver the vehicle to the desired landing target in both simulations with similar throttle profiles, as evidenced by Figure 11a. Similarly, the flight path angle profiles shown in Figure 11c are similar between the two simulations, with differences primarily attributed to the Genesis simulation not modeling the pitch-over maneuver. The POST2 simulation shows the vehicle achieving a flight path angle of -90° (relative to the local horizontal plane), signifying a vertical touchdown velocity. The Genesis simulation shows a flight path angle of approximately -70° . However, as shown in Ref. [34], the desired -90° can be achieved even for 6-DoF trajectories if guidance and simulation planet parameter assumptions (e.g., J_2) are verified to match; however, this was not completed for this work due to time constraints.

Figure 10 and Figure 11 demonstrate the capability of FP²DG to deliver a vehicle to its intended target given the idealistic implementation of converting a commanded acceleration into a thrust vector. A more realistic representation might transform the acceleration command into pitch and yaw angle commands; however, this proved challenging due to the initial definition of body reference frame to support entry phase as compared to the vehicle’s descent orientation of flying backwards. This challenge and others are discussed in Section IV.

IV. Challenges

Several challenges were noted throughout the evolution of this effort. Firstly, the team noted differences in FNPEG routine codebases due to previous project-specific edits and methods of interfacing with simulation frameworks. The team therefore noted the difficulty in performing simulation comparisons with guidance algorithms that do not share common codebases. In addition, due to the initial scope of the task, body reference frame definitions were not stated up-front, contributing to difficulty in confirming vehicle aerodynamics and orientation throughout various phases of flight. The challenges in addressing these obstacles led the team to develop a proposed simulation comparison effort matrix, a first cut of which is shared in Table 6.

Table 6: Simulation effort comparison matrix

Level	Models	Comparison Effort
1	- High-level project definitions of environment and vehicle - Independent implementations of environment, vehicle, and GN&C models	- Co-plotting of performance results - Low-level effort to identify sources of differences
2	- Some shared environment, vehicle, and/or GN&C models - Project definitions of environment and vehicle models - High-level project definitions of GN&C models	- Co-plotting of performance results - Some effort to reconcile differences
3	- Project definitions of environment vehicle, and GN&C models - Majority shared environment, vehicle, and GN&C models - Some subsystem unit tests - Some integrated system tests	- Detailed comparisons of nominal time histories and relevant parameters - Elevated effort to reconcile differences
4	- Shared environment, vehicle, and GN&C models with version control - Shared configuration-controlled inputs of common models - Formal definitions of common coordinate frames - Shared subsystem unit tests - Shared integrated system tests	- Version-controlled outputs with shared plotting routines - Detailed comparisons of nominal and selected off-nominal time histories of dynamics and relevant parameters - Detailed comparisons of statistical performance parameters - Thorough and detailed effort to reconcile differences

The proposed comparison effort matrix attempts to outline both model and comparison effort tasks/definitions required for different levels of comparison, with higher levels associated with more robust modeling and comparison effort. The goal with this matrix is to help categorize validation and verification (V&V) tasks to help define ground rules and assumptions and the overall scope up front to try and mitigate some of the challenge the authors noted during

this task. Note that an effort does not need to share the same model comparison level as comparison effort level. A lower-level model comparison effort might consist of high-level project definitions of the simulation environment (planet, atmospheric model, gravity model, etc), while the highest tier of model comparison levels may include common repositories of guidance algorithm code complete with unit tests to validate inputs and outputs. It might also include formal definitions of common coordinate systems to aid in results comparison discussion. Similarly, a lower-level comparison effort might involve co-plotting performance results and identifying differences and possible causes but not necessarily resolving said differences. Increasing the level of comparison effort might start to include larger efforts to reconcile differences noted in results, shared plotting routines, and investigating statistical performance in said comparison. Note again that the intended goal of defining the simulation effort comparison matrix is to provide guidance for other simulation comparison efforts to help prevent similar challenges faced under this task.

V. Conclusion

This paper investigates the performance of a human-scale, mid-L/D Mars entry vehicle using two independent flight mechanics simulations. Two guidance algorithms were used: the Fully Numerical Predictor for Entry Guidance (FNPEG) was implemented for the entry phase, while Fractional Polynomial Powered Descent Guidance (FP²DG) was used for the powered descent phase. The simulation environments and nominal trajectory results are compared directly between the two simulations, with differences being explored. The simulation environments, notably atmospheric density, and speed of sound, were shown to have minor discrepancies between the simulations, resulting in minor differences in aerodynamic coefficients. However, even with these differences nominal trajectories were shown to be in good agreement, and the FNPEG routine was able to deliver the vehicle to the entry termination point in both simulations. Similarly, the simulations produced similar powered descent phase profiles, namely in throttle command, flight path angle, and vehicle groundtrack. The vehicles landed at the desired landing location in each simulation. An important takeaway from this comparison effort was that the process for comparing guidance algorithm performance was lacking and challenges were noted due to lack of formal ground rules and assumptions defined up front. This led the authors to proposing a simulation effort comparison matrix help facilitate future simulation comparison efforts.

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