Michigan State University

Final Report

NASA/ASU Psyche Mission Landing System for Hypothesized Surfaces

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It is also worth acknowledging that the collective teams responsible for the many aspects of the NASA Psyche mission, including the robotic explorer, in-situ resource utilization, future power solutions, and the landing system (this team) for hypothesized surfaces, met to discuss the overall goal of these projects. The intent in doing this was to create a more cohesive deliverable for the sponsor, and sharing general information regarding each of the projects involved with NASA's Psyche Mission was decidedly the best way to accomplish that.

Nomenclature

Symbol	Meaning	Unit
a	Acceleration	m/s^2
F_c	Centripetal Force	*N*
F_g	Gravitational Force	*N*
F_t	Thrust Force	*N*
G	Universal Gravitational Constant	Nm^2/kg^2
g	Gravity	m/s^2
h	Height	*m*
l	Length	*m*
M	Mass of Psyche	*kg*
m	Mass of lander/spacecraft	*kg*
r	Radial distance/radius	*m*
r_f	Radius from the Center of Psyche to Topological Location	*m*
t	Time	*s*
v	Velocity	*m/s*
v_e	Escape Velocity	*m/s*
v_o	Orbital Velocity	*m/s*
v_t	Tangential Velocity	*m/s*
w	Width	*m*
θ	Angular displacement	*rad*
ω	Angular Velocity	*rad/s*

Introduction to the Problem

In 1852, the asteroid sometimes referred to as 16 Psyche, named for the Greek Goddess of the soul, was discovered by Italian astronomer Annibale de Gasparis. Now, the Psyche Mission led by NASA alongside Arizona State University, seeks to explore this metal-rich asteroid that orbits the Sun and resides within the asteroid belt between Mars and Jupiter. To achieve this goal, a spacecraft was launched from Kennedy Space Center on October 13, 2023, with the intent of reaching and surveying, but not landing on, Psyche in 2029. Modern exploration of Psyche from afar has led scientists to uncover the potential for large amounts of metal to exist among rock throughout its body, producing the concept that it may be a planetesimal core, a remnant of the early solar system. The purpose of exploring Psyche is to hopefully gain a better understanding of how the core of the Earth developed.

The objective of this project is to formulate a manner by which a future mission may physically land on Psyche to conduct further exploration. This process will include performing research on past NASA landing systems to not only analyze their application in this case but to invent solutions to Psyche-specific situations and identify critical criteria. At this point, Psyche's actual appearance and geological makeup are unknown and will remain as such until the launched spacecraft comes closer to approaching the asteroid, though there has been a lot of speculation thus far. Therefore, it is important to research various styles of spacecraft and landing gear to incorporate their relevant aspects into future designs which will be formulated to consider the most likely geological outcomes based on what is known today. Considering that nothing like Psyche has ever been examined up close, it is also important to keep in mind the many variables of touching down on a dense, irregularly shaped, low-gravity body when determining the best features to include in the proposed landing system.

Initial questions for the sponsor/industrial advisor included the scope of the project, deadlines for the team, and goals for sponsor deliverables. The sponsor stated that an acceptable outcome includes usable data, information, and conclusions for other scientists and engineers who may propose to land on the asteroid in the future. The majority of the scope is entirely up to the group as long as it applies to the landing system basis made in the initial informative papers which can be found in **Appendix A**.

Identification of Needs

After speaking with the sponsor regarding deliverables and sponsor-specific needs, what is required of the project results has been clarified. While focusing on a future landing system for Psyche is imperative, it was also made clear that there is no right way to do this as per any preset guidelines, and that there is no specific goal that is required, per se. As explained by the sponsor, the results of this semester must support NASA/ASU's Psyche Mission, as it must explore options within the scope of landing on the metal-rich asteroid. Results of this project may include mathematical calculations and models, a list of compatible parts for a landing system, as well as research in the realm of hypothesized surfaces, etc. but the sponsor specifically required none of those. These, among others, were mentioned in conversation with the industrial advisor, but it was explicitly stated that it was entirely the decision of the group to determine what was advantageous to do, and to what extent. The only requirement the sponsor specifically mentioned was that the material presented must fit within the realm of a Psyche landing system and is justifiably so as per the provided information in **Appendix A**. While this may not seem entirely clear, it makes sense within the scope of the current Psyche Mission. The initial observer-craft that was sent to Psyche in October 2023 will not arrive at the asteroid until 2029, so there are many unknowns about which to learn as it approaches in the coming years before anything finite will be conceivable. This is why it stands to reason that the project scope and end goal are relatively up to the individual group.

Problem Constraints

After serious consideration, it was decided that physically building a small-scale model of a potential Psyche landing system and spacecraft would not be worthwhile. Since the current mission is not set to arrive at the asteroid for approximately five more years, and there is still a large gap in what is understood about the potential planetesimal core, it is plausible that doing research and mathematical calculations with the information that is already available is well founded. Of course, it is important to keep in mind that the asteroid is unlike any NASA has ever visited in that it is metal-rich and will likely require a new approach regarding physically landing on it because of this among other things. The constraints here are many, as it must be understood that, for example, a harpoon may not be effective due to a potentially very hard surface, or that a parachute will not be of much use considering that Psyche has very low gravity and no atmosphere, compared to Earth where such methods would work well.

It is also important to remember that there were only a few months that were available to complete the entirety of this project. One may have wished to complete an entire design for a spacecraft, but that was not realistic. In this case, there were hopes to achieve a gravitational and spacecraft dynamics analysis relating to the asteroid to present it alongside research-based information regarding what sort of craft may be most useful. Other aspects of representation such as small-scale 3D printed models or a fully constructed model were considered. Still, these are outside of the boundaries that are attainable within a single semester considering the amount of designing that would be necessary.

Solution Research and Benchmarking

Much of this project includes the previously utilized products NASA has sent to space, or planned to send to space. The idea of using aspects from past designs being a great way to help NASA save money on future exploration was mentioned early on, and this was heavily implemented into the research efforts. Since the current spacecraft heading towards Psyche includes aspects from previous NASA missions, it only makes sense for this prospective project to do the same. There were resources provided in the form of links and PDF documents from which research commenced, and it was imperative to utilize these sources in starting the research for this project considering that the sponsor supplied them. A summary of preliminary research can be found in **Appendix C.1**, and early design avenues in **Appendix C.2**. From there, comparable systems from previous space explorations were brought into the equation to allow for an analysis of parts to determine which ones would work best in this case. Since Psyche is an asteroid unlike any other that has been visited, there was an overarching wonder if these past works may not prove to be as useful as anticipated. Fortunately, that was not the case based on the hypothesized Psyche conditions, and the research was even able to aid in determining new methods of landing in addition to the modified past aspects that were chosen.

Problem and Solution Impact on Public Welfare/the Environment/Sustainability

This project may only seem like a landing system to reach a never-before-explored region within Earth's solar system, but delving deeper allows one to see that this may impact the way certain processes are done on Earth, too. While a lot of the Psyche Mission's outcomes remain to be seen, it can be surmised that exploring a potential planetesimal core may lead to breakthroughs regarding Earth's core, something that is currently nearly impossible to research with the technology currently available. Of course, it stands to reason that the take-off of a Psyche mission on Earth will impact the environment as much as SpaceX's Falcon Heavy Rocket did in the last Psyche launch, but the rest of the journey is outside of Earth's atmosphere and will not directly negatively impact the environment. While the impact on Earth's atmosphere is important to consider, it is worth mentioning that the scope of this project only includes the physical landing on Psyche, a task which is at that point entirely off-Earth. In terms of risks on Earth, the negative impact of a rocket taking off, as well as a potential waste of resources if for some reason the mission fails, may very well be the only ones in this scenario. The benefits will outnumber the risks considering the above-mentioned hurdles. For example, learning about Earth's origins and core may change the way scientists look at the solar system and Earth as a whole. The mission of landing on and extracting data from Psyche may provide insight into the early solar system which otherwise might have been unattainable.

Concise Problem Definition and Deliverables

A future Psyche Mission that wishes to land on the asteroid includes many different aspects of analysis. For one, mathematical analyses were completed regarding the gravity of Psyche, and then a main mathematical analysis of a generalized landing system was also performed. Research was conducted on past NASA landing systems and from there, a comparison was performed regarding the mathematical analyses to ascertain which designs would be the most apposite. Once portions of previous systems were identified as useful, these parts and designs were analytically brought together to recommend to NASA/ASU what may work best given the most likely of the hypothesized terrain and critical factors on and about the asteroid.

Initial and Contingency Plans

The initial concepts for a potential proposal to return to Psyche with the intent to land on the asteroid included inspiration from various missions past completed by NASA and other space agencies globally. Provided that Psyche is a very low-gravity body, and that there is a lack of exact knowledge regarding the asteroid's makeup, it may prove to be a difficult task to land on it at this point. Following the legacy of prior missions allows NASA to save money on new in-depth research regarding specifics for a new craft, but also allows for certainty concerning mission success. This avenue is the most likely route to success within the scope of this mission.

In 2016, the OSIRIS REx spacecraft left Earth for its target asteroid, Bennu, and upon arrival, it did not 'permanently' land on the celestial body. Instead, OSIRIS REx, using many thrusters to reach the asteroid, employed NASA's first-ever touch-and-go maneuver ("OSIRIS-Rex - NASA - NSSDCA - Spacecraft - Details," 2022). This operation was completed after surveying Bennu for a good landing location and was overall successful. Similarly, on a mission launched in 2003 to Itokawa, another asteroid of low gravity like Psyche, JAXA's Hayabusa spacecraft docked in a touch-and-go style instead of landing more permanently ("Hayabusa Sample Collection Methodology," 2023). This method is a good contingency plan for Psyche if landing is determined to be unfeasible considering that the surface of the asteroid is as relatively uncertain as that of Itokawa was in 2003; it was stated that it was unknown "if the surface was composed of hard rock or soft dirt" ("Hayabusa Sample Collection Methodology," 2023). A depiction of this docking method can be seen below in **Figure 1**, courtesy of JAXA ("Hayabusa Sample Collection Methodology," 2023). These missions have provided the necessary context for the basis of a future Psyche mission, although they are only able to fully give background on impermanent methods of landing.

Figure 1: Hayabusa Docking on Itokawa
("Hayabusa Sample Collection Methodology," 2023)

Of course, it may be desired to actually land on Psyche more permanently, or to eventually even bring a rover of some sort to the asteroid as was done on Mars. In this case, it may be more useful to use design characteristics from the Rosetta mission where the Philae probe was dispatched from the main spacecraft for a more close-up analysis (“Rosetta-Philae - NASA Science,” 2023). In that case, a probe would be dispatched from the orbiter, potentially carrying a rover for more in-depth exploration, and approach the asteroid thereafter. The design of this lander was not initially explored, but it stands to reason that utilizing key features of the Apollo 11 Eagle lunar lander could be critical in maintaining an upright position upon touchdown, utilizing the body design of Philae for familiarity and cost-saving purposes, as well as the potential for a new single-legged design to make use of the friction on the surface of Psyche and make landing more effortless considering the low gravity there.

Analyses

Several analyses were conducted to gain a better understanding of what is to be expected on Psyche upon arrival concerning gravity and other extraneous conditions. First, after an understanding of the low gravity on the asteroid was ascertained, an analysis of the orbiter traveling about Psyche that would dispense the landing system was performed. Another involved the lander itself and the procedure by which it would land on Psyche. A kinematic analysis of the asteroid was also executed, something that is useful for the logistics of the lander. The final analysis was conducted concerning the lander touching down on Psyche. Since there has yet to be up close data gathered, various assumptions were made to aid in some hypothesized calculations. For example, Psyche is rotating about its center and not tumbling, the spacecraft rotates about the equator of Psyche and in the same direction as its rotation, the lander will match the angular velocity of Psyche upon touchdown, the lander will execute a continuous burn of fuel from the thruster, and the surface gravity of Psyche is the mean surface gravity at all points chosen for landing.

To be able to complete these analyses, some constants and various information were provided by NASA, while some were already known. The values that were given are shown below in **Table 1** as well as orbital distances in **Figure 2.**

Table 1: Known values of Psyche

Parameter	Value	Unit
Mean surface gravity	0.144	m/s^2
Universal Gravitational Constant	6.67E-11	Nm^2/kg^2
Length	279000	m
Width	232000	m
Height	189000	m
Radius	116000	m
Mass	2.72E+19	kg

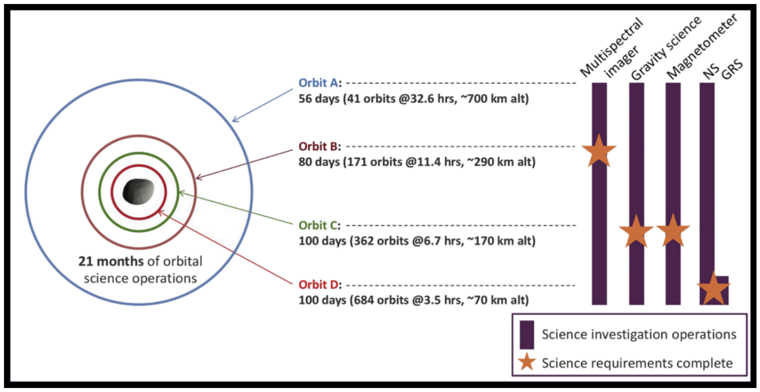


Figure 2: Data of Orbital Distances

With these values, as well as a chosen orbit of orbit D, a calculation of the spacecraft in orbit could be completed. Using the closest orbital distance that NASA projected, the force of gravity on the spacecraft was computed by using Equation (1).

$$F_g = mg = \frac{GmM}{r^2} \tag{1}$$

With the mass of the spacecraft canceling having r set equal to the width of 116000 m and the addition of orbit D being 70000m , the acceleration due to gravity at that orbit was found. To show that acceleration due to gravity increases, Equation (1) was also utilized in constructing a code to find the acceleration due to the gravity of the lander as it is heading toward the surface. The velocity needed for the spacecraft to be able to orbit Psyche was found using Equations (2) and (3)below.

$$v_o = \frac{2\pi(r+r_{f-})}{t} \tag{2}$$

$$F_c = \frac{mv^2}{r} \tag{3}$$

In Equation (2), the sum in the numerator is the distance from the orbiter to the center of Psyche, which is the radius and the orbital distance chosen of 70000 m, and in the denominator is the number of hours for Psyche to make one rotation converted into seconds. Equation (3) is the equation to solve for centripetal force. Using Newton's Second Law of Motion, Equations (2) and (3) were set equal to each other and velocity was the velocity was solved for. The 2 equations produced values of 92.75 m/s and 98.6 m/s respectively, the latter of which was chosen to better suit the centripetal force going inward towards the center of Psyche and have a higher chance of staying in orbit. This orbital velocity may also be described as the tangential velocity at any given point in the orbit. The angular velocity of the spacecraft was calculated by using Equation (4).

$$\omega_{space} = \frac{v_o}{r} \tag{4}$$

Where r is the distance from the spacecraft to the center of Psyche. This was used in the code as an initial angular velocity for the lander once it was ejected from the spacecraft.

The next set of calculations involved the kinematics of Psyche itself. The linear and angular velocities of Psyche had to be measured under the assumption that it is not tumbling and that it is moving in a straight line, basically assuming one-dimensional motion. The angular velocity was found using Equation (5) as shown.

$$\omega_{psyche} = \frac{\Delta\theta}{\Delta t} \tag{5}$$

The change in time shown is the amount of time in seconds for Psyche to make one full rotation, and the angular displacement is the circumference of Psyche. The linear velocity in this analysis was found using Equation (2).

The next and most important step was to emulate the process of the spacecraft landing on Psyche. This was accomplished by employing a Matlab code, the specifics of which are provided in **Appendix C**.

Several equations were used to be able to successfully simulate the landing.

$$r = r_f + 70000 \tag{6}$$

$$v_e = \sqrt{\frac{2GM}{r_f}} \tag{7}$$

$$v_t = \omega_{space} * r_f \tag{8}$$

All of these are fundamental equations that can be solved by hand, however, their values were needed to be able to solve a first-order differential equation (ODE) which is best done iteratively utilizing a code. The use of a thruster was required to induce about 0.05 N of force in the opposite direction of motion to impede the velocity of the lander to prevent crashing onto Psyche's surface which is shown in **Appendix C.1**. This value of the thrust force was determined through trial and error of running the code and seeing the trajectory in which it landed. The manner in which the lander descends resembles a spiral as shown in **Figure 6**, meaning that it is orbiting Psyche as it lands, but the distance between the two decreases. The asteroid staying at a lower velocity than the spacecraft is moving prevents the lander from remaining in orbit.

The final step was to analyze the lander once it had landed. The code allowed for the simplification of this particular analysis. The final velocities and positions, both angular and linear, are shown on the generated graphs displayed in the following section. These graphs allow for the understanding that, after having used the thrusters to slow down, the lander will still have an average final velocity of 59.6 m/s. To compensate for this, the legs of the lander, whether there is one or three, will be equipped with a damper to assist in absorbing the velocity. To do this, the spring-mass-damper system that is the lander will be a critically damped system to completely rid of the velocity and ensure a less-than-damaging landing.

The bulk of these results are generated via code, but to ensure that both the equations and the code could work together, a hand calculation was performed and is provided in **Appendix C**. Most of the values that are supplied in the above equations can also be found in this appendix. These equations were fundamental in figuring out a way to successfully, albeit with numerous assumptions, orbit and land an unmanned spacecraft on Psyche.

Code Generation

The initial mathematical analysis was meant to support understanding Psyche, how it interacts with its environment, and how one can interact with it. This led to the creation of a Matlab code that would predict how the system would function over time, supplying a simulation of landing on the surface. It shall be acknowledged that this code does not account for all possibilities within the task of landing on a celestial body in space. Additionally, it does not account for all of the unknowns of Psyche. This code was assembled to function as a building block that can be added upon when more is discovered about the asteroid.

The base of the code is established by the assumptions that are made. The assumptions utilized correlate with the assumptions acknowledged in the analysis above. These are made to justify the way calculations are made and to fill some of the unknowns that come with a faraway asteroid like Psyche. The only additional assumption that was employed in the code was to treat Psyche as a stationary object that does not have a rotational velocity. The reason for this is to allow Matlab to solve the ODE equation without having to consider the relationship between the rotation of Psyche and the lander. If this relationship was accounted for in Matlab, it would make the code much larger and the run time would likely be too large for Matlab to tolerate. This lack of rotation was included after the Matlab outputs were gathered.

For the code to function, there needed to be a manner by which to tell the computer where the lander wants to go. This was solved by generating a coordinate system using longitude and latitude and setting it to Psyche's surface. From there, five desired zones were chosen using numerous topography maps to locate suitable landing locations for the designs chosen. These specifics can be seen below in **Figure 3** (Shepard, 2021, p.10) and **Figure 4** (Jaumann, 2022, p.9).

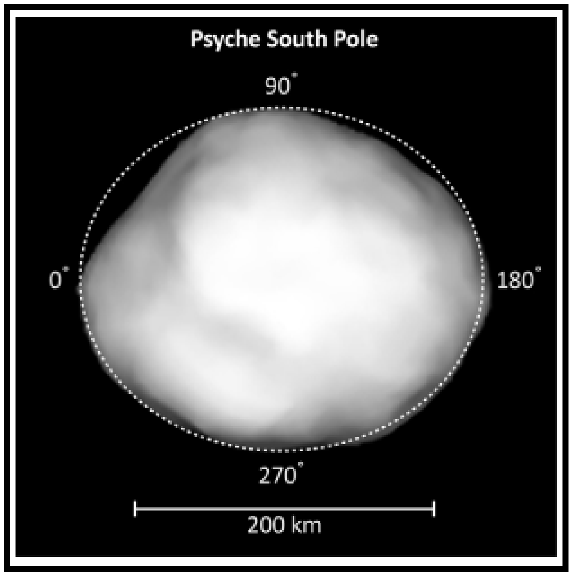


Figure 3: Longitude Coordinate System of Psyche
(Shepard, 2021, p.10)

To help specify the coordinate system and the diagrams used to establish it. The photo seen in Figure 3 is a mapping of the Psyche South Pole based on rough data and assumptions. This displays the South Pole coming out of the page. The axis of rotation is assumed to be aligned with the North and South Pole.

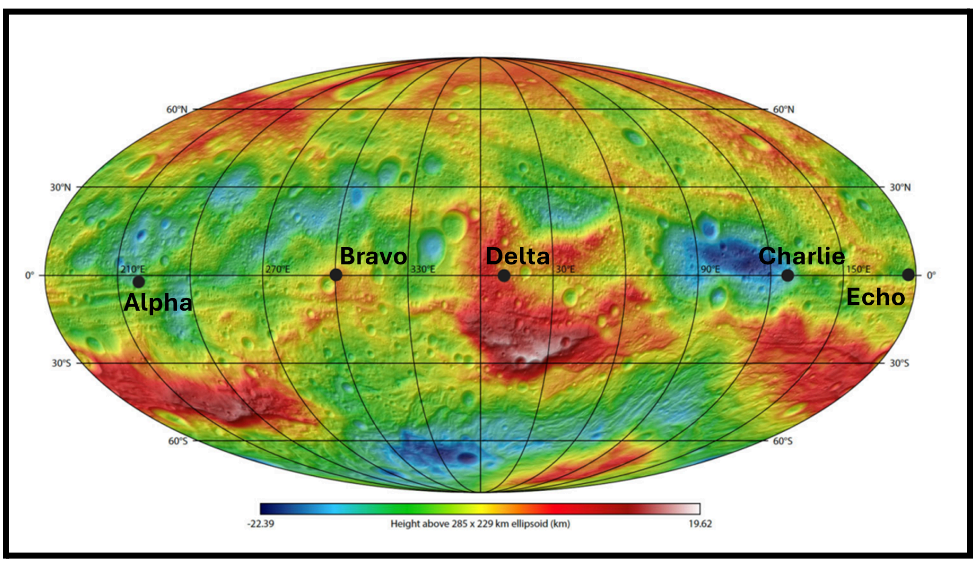


Figure 4: Landing Locations on Psyche
(Jaumann, 2022, p.9)

For each established landing site, the radius to the center of Psyche was needed to understand how the lander would travel to reach the desired location. This was done by calculating the change in shape in the assumed oval at each angle while also accounting for the diverse topography. **Table 2** shows the final radius for each corresponding location.

Table 2: Location Angle and Radius

Location	Longitude	Radius (m)
Delta	10	146070.9
Charlie	130	124185.4
Echo	180	147000
Alpha	220	123183.4
Bravo	300	120750.5

This radius, along with the angle, supports the framework to establish whether the code would be successful; if the coordinates are reached at the matching radii, then the only item to concern oneself with is velocity.

In the code, the locations were called out using an input function that allows the user to select one of the longitudinal coordinates. This was done using the code in **Appendix C** shown in **Figure C.3**. Once the code receives an input, it runs Equations (1), (6), and (7) to calculate and display the essential Psyche data that is specific to that location. The Psyche data is calculated first to understand how the surface will present and what the constraints are in that spot. For example, the lander cannot land at a velocity greater than the asteroid's escape velocity, or it will bounce off of the surface at that location.

The body of the code is an ODE equation that relates four separate differential equations to each other and solves for all four unknown variables across a desired landing timespan. The four differential equations were derived from a free-body diagram (FBD) analysis of the lander while rotating about Psyche. This derivation can be seen in **Appendix C** in **Figure C.2.** The forces balanced in the FBD are the force of gravity and the centripetal force which are the only assumed forces present in the system. The complexity of the problem and the ODE equation used is because of the change in gravity as the radius changes. This creates an unknown, changing variable in both force equations that relate to one other. To combat this, the equation of motion was derived for the 'r' and 'theta' directions and used to solve for the unknown variables. The ODE function is used in Matlab because iteratively solving four equations for four unknowns over a timespan of thousands of seconds would take too long by hand. The two sections of the ODE function in Matlab can be seen in **Appendix C** in **Figure C.4** and **Figure C.5.** The lines in **Figure C.4** show the initialization of the ODE and the parameters that the user can give the ODE to work with. The ODE equation comes from the origin of the free body diagram of the lander that was conducted which can be seen below.

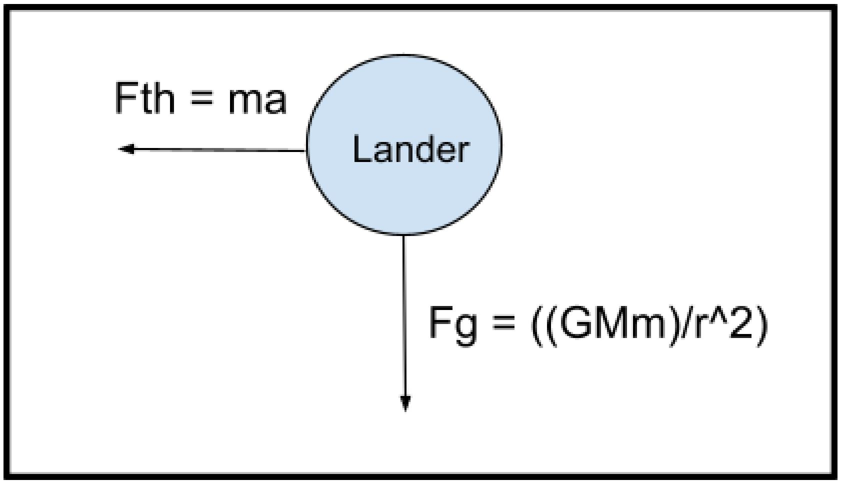


Figure 5: Free Body Diagram of the Lander

As a result of this free body diagram, there were two forces determined to act; the force of gravity and the thruster force of the lander. The two forces were then broken down into the factors that make them up by accounting for the various accelerations and velocities. The variables and equations are taken in respect to the lander so each velocity and acceleration is some trait of the lander. To break down **Figure C.2**, the gravity force equations account for the force that gravity applies plus the change to the centripetal force. This centripetal force is accounted for by multiplying r and theta dot. The thrust force equation is a relationship of the angular velocity and angular acceleration to the velocity of the lander. These two force equations can be used to solve for the four individual variables: position (r), position (theta), velocity (r_dot), and velocity (theta_dot). They are solved for by writing the two force equations in terms of the two accelerations present. The theta acceleration is solved using the thrust force equation. The r acceleration is solved for using the gravity force equation. From this process, there were four equations and four unknown finds which can be used to solve for each variable. The reason for the ODE in matlab is because the variables are being solved for over a large timespan which would take too long by hand. In order to place the equation in an ODE in Matlab there can only be one variable used for each equation. For this reason, the r is treated as x1 and related to the r_dot by saying x1_dot=x3 where x3 is r_dot. This is done for the theta variable as well and each of the renamed variables are substituted into the proper equation.

The timespan tells the code for how many seconds the ODE should find the solution. The line below the timespan represents the initial conditions for each variable being solved. In this bracket, the user can set the initial conditions to whatever is desired. **Figure C.5** shows the second half of the ODE, this is where the four equations are established and if there are any constants or outside values that are needed in these equations. The ODE allows for a fast derivation and display of relations for all variables over a large timespan to ensure accurate data outputs for all four variables.

Two key parts in the solution are the force variable which can be seen typed as ‘Ft’ in the code, and the mass variable displayed as ‘m.’ The mass variable represents the mass of the lander, a value which is assumed to be 265 kg based on the masses of previously used landing systems. It shall be acknowledged that the change in mass due to burning fuel was not considered due to the highest change being less than 4% of the total mass. The force variable was solved in the equation of motion as the thrust that the lander should produce in the theta direction. This thrust force is the only way to slow down the orbit of the lande and induce a 'fall' toward Psyche. The force is used in two phases, the low thrust phase and the high thrust phase. The low thrust phase is a 0.05 N force at the beginning to induce a slow spiral toward Psyche. The high thrust phase occurs at the very end of the orbit to slow the lander down and match the rotation of Psyche itself. This is done by comparing the output rotational velocity to the known Psyche velocity. The variables that result in the best-suit landing procedure, as well as the output graphs for one location, can be found in the results section.

Results and Justification

The approach for the code was to start at the initial orbit and from there understand how different thrust forces for different time periods make the lander behave. The design takeaway would be the concept of what thruster and what fuel is needed to produce the desired forces. The code also produces insight as to how the lander is going to contact the surface. It allows for the design to consider what may be needed to counter any unexpected forces or velocities.

The tables seen below display the results from the code and further calculations. These results walkthrough how the lander would operate and interact with Psyche. They give a good indication as to how the design of the lander should prepare for various approaches and landing procedures. Psyche is a challenging obstacle with a surface that exhibits many variables and it was important to take this into account when writing this code.

Table 3: Inputs for successful landing flight at each location

Location	Longitude	Radius (m)	tspan (s)	theta	Low Ft (N)	High Ft Time (s)	High Ft (N)
Delta	10	146071	33380	-0.3	-0.05	31960	-9.4
Charlie	130	124185	35460	0.75	-0.05	33690	-10.2
Echo	180	147000	35400	1.4	-0.05	34030	-9.5
Alpha	220	123183	35460	-4.3	-0.05	33670	-10.2
Bravo	300	120751	35460	-2.6	-0.05	33650	-10.4

In **Table 3**, there are 5 distinct locations listed, and it is because of Psyche's unusual shape that they all possess a different radius. The radii at each location can be thought of as an altitude value. For each altitude, there is a different path and approach to applying a thrusting force that must be considered to reach the same angular velocity as Psyche, bringing the angle of approach into question. Additionally, the theta for each location instructs the lander at what longitude in radians it should commence the landing sequence. It can be observed at Charlie, Alpha, and Bravo, that the altitude is much lower than the mean radius of Psyche, meaning that these areas present a risk of crashing into Psyche before reaching the landing zone. For this reason, and to match the angular velocity of Psyche, a low thrust force and high thrust force were used. The low thrust force remained the same for each approach with only a varying time span, while conversely the high thrust force was altered to achieve the ideal angle and match the angular velocity as best as possible. In the table above, the ideal inputs for landing at each location are listed. The high thrust force encourages a steeper landing path that decreases angular velocity and ensures a straight path downward. It is important to note that both high thrust and low thrust are relatively small and that the various time spans for each are significantly large and equate to an approximately nine-hour landing sequence. These inputs for each landing spot were found using a trial and error based approach where the force variables and timespan would be changed until the radius and Psyche rotational velocity was closely matched. When comparing these inputs to past landing missions, they proved to be feasible. The landing projection, velocity vs time plot, and position vs time plot, both for location Delta, are shown in **Figure 6** and **Figure 7** below. The outputs of the code that result from each of the ideal inputs can be seen in **Table 4**. The desired outputs for each location were the escape velocity (Ve), the final radius (Rf), the final radial velocity (Vf), and the final omega for the lander.

Table 4: Outputs at each location

Location	Longitude	Ve (m/s)	Rf (m)	Vf (m/s)	Omega final (rad/s)
Delta	10	157.6088	145945	-39.8813	0.000434112
Charlie	130	170.9334	124199	-70.8117	0.000435132
Echo	180	157.11	147013	-38.5688	0.000433813
Alpha	220	171.6273	122786	-72.6968	0.000438892
Bravo	300	173.3476	120647	-76.0922	0.000435341

To justify a good landing sequence, the three goals in mind included landing at the corresponding radius, landing near the Psyche omega (0.0004363 rad/s), and landing with a velocity less than the escape velocity. These were accomplished for each by altering the high thrust force and the time span until the desired outputs were relatively correct. It can be justified when the lander touches down within a reasonable radius when compared to the radii in **Table 3**, when the lander touches down with a velocity lower than the escape velocity, and when the omega final for each location also matched relatively well. It is important to note that the omega value found here may include some error when compared to the actual Psyche omega value. The overall error in this landing system code is addressed later.

Within the code, the lander is assumed to reach the surface with the velocity depicted in **Table 4**, but to actually land with this velocity could fail. To combat this, the thrust force needed to slow down the lander to a near-zero velocity was calculated using the impulse equation with a constant time variable of 20 seconds. This time variable was chosen because it is a good mean value such that the elevation was not too small or too large.

Table 5: Thruster Force for landing with a small velocity

Location	Longitude	Radius	Meters Above Surface	V1 (m/s)	Time (s)	Ft (N)
Delta	10	146698	753	37.5661	20	497.750825
Charlie	130	125545	1346	68.9226	20	913.22445
Echo	180	147734	721	37.4439	20	496.131675
Alpha	220	124249	1463	70.7526	20	937.47195
Bravo	300	122028	1381	74.1085	20	981.937625

Table 5 displays the distance above the surface that the thrust force shall be applied in the radial direction to slow the velocity down over a time of 20 seconds. This class of procedure could be programmed into a landing system's code to instruct the lander when to operate. The thrust force calculated for each location was significantly dependent on the velocity 20 seconds before landing which is displayed as V1. To alter the thrust force needed, the time at which to act could be increased which would allow for a longer time to bring the lander to a halt. The smallest force values needed occur at locations Delta and Echo, sites which could be ideal for landing a rover. The areas that require larger forces would be ideal for a collection device that bounces off the surface, but in these zones, it may still be possible to land.

The final table below, **Table 6**, complements the code results and supports the idea of predetermined landing locations that can be programmed into a potential landing system. In the code, the rotation of Psyche cannot be accounted for or displayed in any way, so it had to be executed separately. This was done by collecting the total time span of each location's landing procedure and multiplying it by the rotational velocity (ω). Since Psyche's theta value is so large, it was divided by 2π to show how many times it completed a full rotation, a value which on average was roughly 2.45 times. The two full rotations were taken out of the equation because only the offset angle from equilibrium was desired, and this was calculated by subtracting the Psyche theta value by two and multiplying the remainder by 2π.

Table 6: Starting position for launch sequence

Location	Longitude	Total Time	Psyche Omega	Psyche Theta	Offset Theta	Starting Position
Delta	10	33380	0.000436	2.316290112	1.987309386	1.687309386
Charlie	130	35460	0.000436	2.460624547	2.894189386	3.644189386
Echo	180	35400	0.000436	2.456461054	2.868029386	4.268029386
Alpha	220	35460	0.000436	2.460624547	2.894189386	-1.405810614
Bravo	300	35460	0.000436	2.460624547	2.894189386	0.294189386

The offset angle shows how inaccurate the longitudinal zero about which Psyche rotates is by the time the lander touches down. The offset angle was accounted for by adding it to the starting theta of the lander, found from the code seen in **Table 3**, which resulted in the starting position. This starting position is the true theta in radians from the longitudinal zero that the lander should begin its landing sequence to touch down at the desired locations.

In addition to the data demonstrated in the tables above, the code also delivers two figures, one being a graphical analysis and the other being a landing path projection. These figures help showcase what is ensuing throughout the complete landing sequence to ensure no unexpected errors occur.

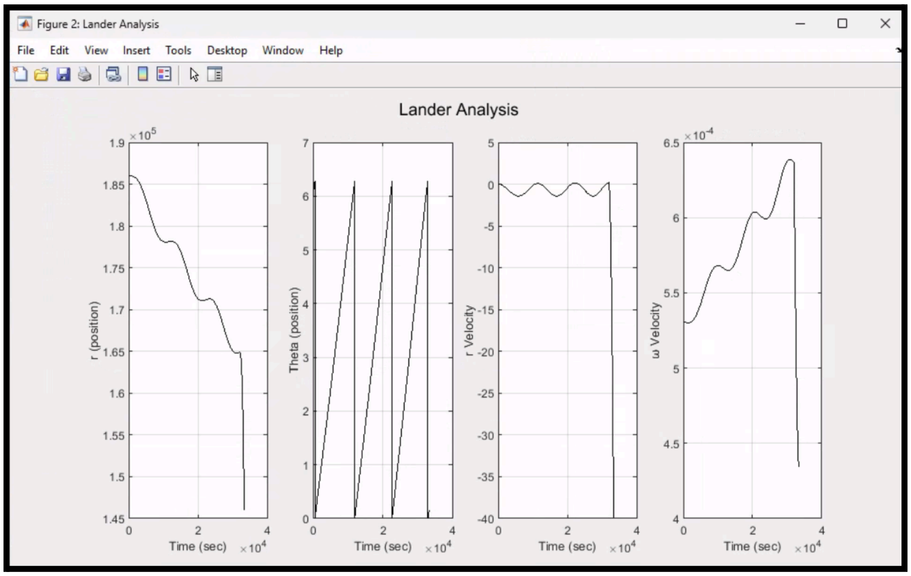


Figure 6: Graph Lander Analysis at Location Delta

Figure 6 above was utilized to match position and omega values to ensure a smooth landing on the surface. The order of graphs from left to right is r-position, theta-position, r-velocity, and omega. As time increases there is an observed change in trend between the r-position, r-velocity, and omega when the higher thrust force is activated. As discussed above, this was completed to drastically increase the omega value to match that of Psyche. In the fourth graph, it can be seen that omega changes from a rising slope to a sharp downward fall to correspond with the approximate omega. When the high thrust force variable is changed it results in a different position, omega, and r-velocity. It was observed that the thrust force was proportional to the r-velocity and position but was the opposite for omega, meaning that finding the perfect force and timespan to balance all three variables took time. It shall be observed that there is slight fluctuation in the graphs which is due to the small imperfection of the initial orbit. This imperfection is due to the irregular shape of Psyche and the inability of MATLAB to account for the smallest changes in velocity needed to create a perfect circular orbit. The imperfect/fluctuation is because the orbit is slightly elliptical and MATLAB is measuring this small elliptical character. This has no effect on the final results as the code is calculating for this change in orbit and the forces applied would still create the same result from the same starting position and velocity.

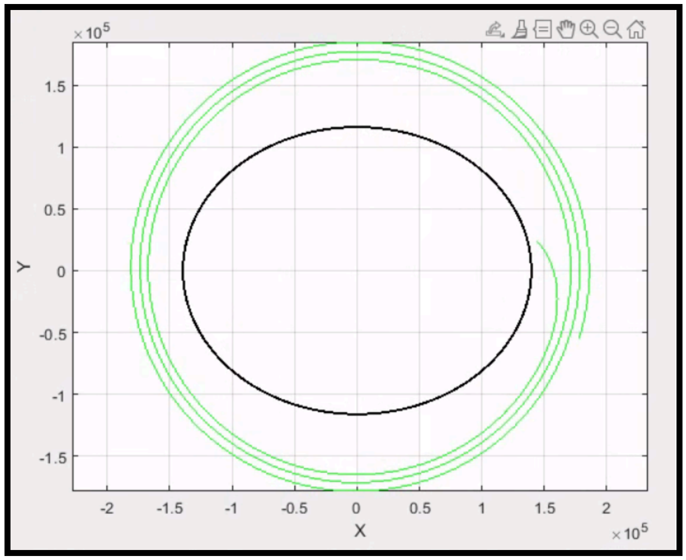


Figure 7: Landing Trajectory at Location Delta in 2-Dimensions

A trajectory of what the path would look like to land at location Delta is illustrated in **Figure 7** above. The lander path is the green line while the black oval is a 2-dimensional representation of Psyche. It is crucial to remember that Psyche is neither a perfect nor a smooth oval, meaning that, although the path may not visually connect with the asteroid on this graph, the lander would touch down on Psyche's surface. This path ensures a clean entry on the surface at a minimal speed while also minimizing the fuel required and employed, this is to say that less mass is consumed by and less money is wasted on fuel. The choice to visually represent this trajectory was decided upon because envisioning what the lander would do was deemed essential. The visualization allowed the team to see if the lander was crashing or spiraling off into space or to catch if any other sort of error occurred.

The Matlab code and the data collected allow there can be investigations made about the fuel type, fuel usage, and delivery. The fuel type required is divided between the two different burns, one needing to burn for a long duration while outputting a small amount of force. This suggests it would be ideal to use some sort of electric propulsion mechanism to save money on fuel and allow for a longer usage period. The other fuel for a low thrust scenario is a hall-effect ion thruster that outputs about 0.055N of force per engine for a duration of 2000s, as seen in **Figure C.6** ("4.0 in-Space Propulsion." 2024). To make the force constant, four thrusters will be required on the side of the lander; this kind of thruster limits the amount of fuel needed to the point that the mass of the fuel is less than 1% of the total mass.

The higher thrust force was a big concern at first because a key aspect of the design is to limit fuel usage so as to limit money and mass change, the thruster and fuel chosen for this application can be seen in **Figure C.7** ("Hydrazine Thrusters" 2024). This thruster uses hydrazine monopropellant to produce a maximum of 28N of force. The average force needed from this thruster is less than half of 28N, meaning that a lot of fuel is saved by burning the thruster at half force. Another positive is that only one of these thrusters is fully needed, which saves space and mass, and the amount of mass lost on this thruster from the burn is less than 4%. It may prove ideal to include one of these thrusters on each corner or side to be able to enact corrective course action.

The final force for which to compensate is that which is needed to slow down the lander in the radial direction to safely land on the surface. The force shown in **Table 5** is larger and requires multiple thrusters to create a steady, uniform thrust, while an ideal thruster for this case would be a hybrid chemical propulsion system that produces approximately 222N of force. The ideal system would require attaching four thrusters equally distributed throughout the bottom of the lander. The fuel used in this system would make up more mass than the other two, but it would not be used until the landing sequence, during the last 20 seconds of landing, and for this reason, the change in mass is ignored. All three of these fuel types are common in landing systems and prove to be a useful solution to the issues the lander will encounter. When comparing these fuel types to those that are commonly used, they are the same or very similar.

As the code is solved upon being prompted, it takes the input feature provided by the user and predicts the path of landing using constant assumptions and factors that are cast over the time span. One of these constant factors is the thrust force that is applied in the theta which is subject to change. This code could be utilized as a building block for a feedback loop system that would be input into both a computer and laser altitude tracker on the lander. This would be done to create a landing sequence on the lander to limit the amount of communication needed from Earth to the asteroid considering the radio time delay. The thrust force variable, instead of being a constant preset value and then guessing where the lander will land, can be a function of the velocity and angular location. The velocity and location would be read using a laser and the force would be calculated and applied based on this feedback. The code could be written to input where the lander wants to land and at what speed to then deduce the sequence from that point. This would reduce the amount of error involved because it would allow for corrective action based on feedback every second of the landing process. Considering that much is unknown about Psyche, the code must make a lot of assumptions to produce an output; it is imperative to note that these assumptions may be false. To improve this code once more is known about Psyche, new data can be added to it; this was the goal for the code from its conception, to be a building block. While it was able to produce a landing sequence that may prove successful given the assumptions made, it must be known that this code is the beginning of a much larger project.

Concept Design and Recommendations

The design of this potential future spacecraft for landing on Psyche has gone through many iterations including various device and aspect inclusions deemed potentially necessary. Supplementary design aspects of the landing gear, like communication & visualization, can be found in **Appendix C.3**, while collection devices & added parts are seen in **Appendix C.4**, and alternate design inclusions are in **Appendix C.5**. For the specifics on the landing gear, though, one might look to past lunar landing missions for inspiration. Although the gravity on Earth's

Moon is much higher than that of Psyche, it stands to reason that the design of the landing gear may prove helpful in navigating a potential protoplanet with a hard, broken-up surface. The manned lunar landing mission Apollo 11 utilized three legs with round footpads ("Apollo 11 Lunar Module / EASEP - the NSSDCA - NASA." 1) to prevent tipping and aid in a proper landing. Of course, this type of lander will not be as useful in the case that this mission wishes to deploy a rover on Psyche. Then, it may make more sense to employ a one-legged lander, something which resembles a sled. In the case that a permanent landing on Psyche is deemed undoable for any reason, it may be necessary to employ a touch-and-go system.

While the Apollo 11 Lunar module Eagle, seen below in **Figure 5**, was much larger than what is required for Psyche, as Apollo 11 was manned and needed space for human life, its leg design may be quite useful in a landing mission to the asteroid. Considering the porous regolith and relatively large gravity on the Moon as compared to Psyche, it made sense to utilize this design feature, and for Psyche, it's reasonable to use them as well but for different reasons. The exact composition of the potential protoplanet will remain unknown until the current mission arrives, and it is expected to see a rocky, not flat surface upon arrival. Keeping this in mind, a hemispherical pad beneath the legs of the lander makes sense regarding avoiding tipping considering the larger surface area and therefore providing a larger reaction time. In addition, a round end-of-leg design allows the lander to touch down somewhere that may not be the flattest and still be successful, especially knowing that this landing mission would be entirely autonomous and without human guidance.

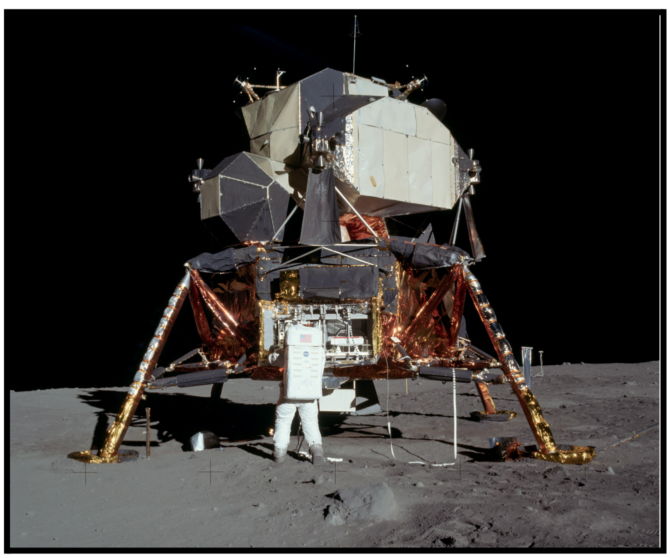


Figure 8: Lunar Lander Eagle from the Apollo 11 Mission with Round Footpads
("View Apollo 11 Lunar Module as It Rested on Lunar Surface." 2018)

The term 'sled' used in the context of a lander is meant to be loosely interpreted as a one-legged device. This is to say that a single-legged lander would serve the purpose of providing more surface area upon making contact with Psyche and therefore make tipping less likely. This style somewhat takes inspiration from the touch-and-go method, but overall aims to incorporate a spring-damper system to absorb rebound and prevent the lander, the mass, from ricocheting off of the surface. The increase in surface area also increases friction and serves to eliminate the horizontal velocity of the device as it lands. The downside to this style is that a rocky or rough surface would make it difficult to find a flat landing location, especially keeping in mind the fact that Psyche has many hills and valleys. This design choice is likely only applicable in an ideal scenario in which there is a clear, unobstructed area on the surface. This style, likely for this reason, is not common among past landers.

As seen in the Hayabusa mission to the asteroid Itokawa via JAXA explained in further detail in **Appendix B.2** through **Appendix B.5**, it is also possible to use an impermanent lander for Psyche. This style utilizes a touch-and-go operation in which it does not remain on the surface permanently for any extended period. The main goal of a design like this is to collect materials from the surface. The mission to near-Earth asteroid Bennu utilized a successful touch-and-go maneuver recently, and OSIRIS-REx partially returned to Earth with the samples afterward, also explained further in **Appendix B.2** through **Appendix B.5**. This is a good option for Psyche in that it allows for material experimentation and classification on Earth, but it is likely less feasible considering that Bennu is much closer to Earth than Psyche is.

Conclusions

From the many options available, assuming that conditions are as they have been assumed to be up until this point and throughout the analysis, the Apollo 11 Eagle rounded footpad style would be best in the scenario that tipping is a considerable concern, especially knowing that the lander will be autonomous. On the other hand, a sled or one-legged lander style would make more sense when it is desired to utilize the friction of the potential protoplanet while also assuming that Psyche possesses more of a flat surface than is anticipated currently. Lastly, a touch-and-go style would be best in the case that landing permanently on Psyche is deemed unfeasible for whatever reason. Overall, the results of this research and analysis are highly dependent on the hypothesized scenarios presently being implemented. While not everything is theoretical, it is safe to assume that most of the essential particulars will not be fully known until the current mission makes it to Psyche in the coming years.

Appendices

Appendix A: Initial Information

Below in **Figure A1**, the initial provided information for the NASA Landing System for the Psyche Mission through ASU can be seen. It was provided initially by the sponsor that the selected team must design a system that can be used in varying hypothesized surfaces that may be found on the asteroid.

MICHIGAN STATE UNIVERSITY

design program

Department of Mechanical Engineering
Return to Jim Lang, ME481 Capstone Coordinator: langjame@msu.edu

Project Non- Confidential Project Summary
Distributed to all ME 481 Capstone design students for review. Students provide project preferences to course faculty.

Project Title: Landing System for Hypothesized Surfaces
Project Technical Contact (Name & Title): Cassie Bowman, Associate Research Professor
Technical Contact Email and phone # c.bowman@asu.edu; 480-727-2219

Questions you may want to address in your summary include: If students may not be familiar with your company you may want to include a couple of sentences describing your company or division. What is the problem you hope to solve with this project? What are the project objectives? What is the scope of the project? Are there any specific skill sets or tools that will be required? Describe how this project will positively influence your company through, for example, reduced costs, a new product, higher quality, faster production, a healthier workplace etc.? Feel free to include pictures or graphics.

The NASA Psyche Mission is an orbiter mission to the metal-rich asteroid, Psyche, in the asteroid belt between Mars and Jupiter. The spacecraft, launching in October 2023 and arriving at the asteroid in mid-2029, will study the asteroid from orbit and will not land on the surface. It is possible to imagine, however, that after learning about Psyche from orbit, there may be scientists and engineers interested in proposing a future mission to land on the asteroid.

In this capstone project, you are that team! Designing to the range of hypothesized surfaces and terrain that might be found at Psyche, which have been laid out in recent scientific reports (and keeping in mind other constraints such as its gravity), you will design a landing system capable of safely landing on Psyche. Hypothesized surfaces and terrain may include: mostly flat metallic surface, flat metallic with metal and/or rocky debris, rough/high-relief metallic and/or rocky terrain, high-relief metallic crater walls. Specifications will be provided for the team to inform the design.

ABOUT PSYCHE CAPSTONE: This is an exciting opportunity to test your design skills, problem solving, and creativity! You will become part of a larger community of students working on a range of projects with Psyche and have the opportunity to meet members of the Psyche mission team. We look forward to having you become part of the Psyche team through this unique capstone project.

Figure A1. Sponsor's Initial Description of Project

This work was created in partial fulfillment of Michigan State University's Capstone Course "ME 481". The work is a result of the Psyche Student Collaborations component of NASA's Psyche Mission (https://psyche.asu.edu). "Psyche: A Journey to a Metal World" [Contract number NNM16AA09C] is part of the NASA Discovery Program mission to solar system targets. Trade names and trademarks of ASU and NASA are used in this work for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by Arizona State University or National Aeronautics and Space Administration. The content is solely the responsibility of the authors and does not necessarily represent the official views of ASU or NASA.

Appendix B: Miscellaneous Data & Research

To display what Psyche looks like, a 3D-printed model of the asteroid was produced using the 2017 Shepard Model (Elkins-Tanton, 2017). While this is not the newest version of the Shepard mode concerning the composition of the potential protoplanet, it is the currently used shape model. Additionally, a representative Philae probe model from the Rosetta Mission was designed by the team and printed out to display one of the many lander options and to highlight the round footpads discussed and featured on the Apollo 11 Mission.

Appendix B.1: Preliminary Research

Before research began, it was imperative to select areas of importance and thereby narrow down what information was the most necessary to delve deeper into. For instance, understanding the geological makeup of Psyche, the temperature range on the asteroid, as well as the shape and rotation of the body are all crucial to keep in mind when designing a landing system for a potential prospective mission.

Psyche has been classified as an M-type asteroid (Dibb, 2022, p.1573); this taxonomic nomenclature system uses color spectrum reflectance data to categorize asteroids while also classifying them considering materials data gathered from their reflectance spectra. This means that Psyche specifically should be composed of mostly metal constituents, in this case mainly iron and nickel (Shepard, 2021, p.1). However, recent reflectance spectrum data shows the asteroid as being a Fe-rich pyroxene, meaning that it is likely there may be silicates present within its makeup as well (Dibb, 2022, p.1583). This is something that is seen in the EIII subtype of Tholen E-Type asteroids and suggests that there is more to be learned about M-types, and therefore Psyche as well (Dibb, 2022, p.1571). It is the hope of the current Psyche mission to gather up-close data to supplement such hypotheses, among other things, to broaden the knowledge base on this asteroid and perhaps others. The classification of Psyche in this manner is important to note because the question of how to approach landing on an asteroid may be significantly altered depending on the materials present on and within the asteroid. While older data on M-types explain that there should be large amounts of solely metal present on the surface of Psyche (Dibb, 2022, p.1571), more recent data allows for the conclusion that Psyche's surface consists of both metal and silicate components (Shepard, 2021, p.2), something which is likely indicative of a protoplanet.

As with any space mission, temperature needs to be accounted for when it comes to selecting a material from which to construct a spacecraft. The baseline temperature in outer space is approximately 3 K, so this is where the details of design will begin, but it is also important to note what temperature the body of Psyche will be upon future arrival. Studying Psyche from afar has led to estimated surface temperatures throughout a day and year on the asteroid, but this information will only be further solidified or perhaps altered when the current Psyche mission collects more data in a few years. The estimates for the future temperatures on the surface of Psyche in 2026, as seen below in **Figure B.1** (Bierson, 2022, p.4), include an approximate maximum temperature of 250 K and an approximate minimum temperature of 55 K. In **Figure B.1**, the vertical black line in c) corresponds to a) and b) times, where the colors present correspond to the latitude values provided in a), and the depth axis refers to the depth of the asteroid. With these values, material selection can be more easily made.

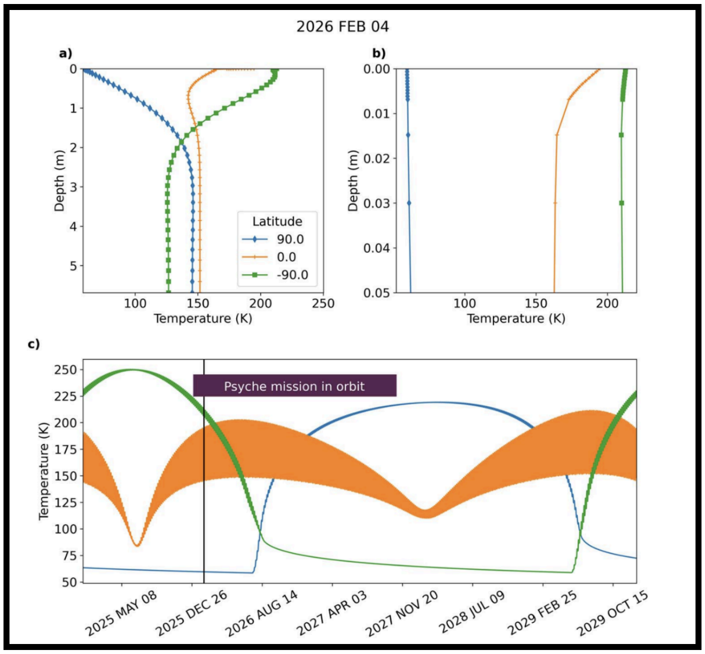


Figure B.1: Estimated Future Daily and Annual Temperature Ranges on Psyche from Bierson
(Bierson, 2022, p.4)

There are not currently any actual images of Psyche, as these will come later when the current mission approaches the asteroid and can capture some. However, the technology that is currently available has allowed for rough approximations of what is expected upon arrival, and such insights will prove useful for hypothetical landing missions in the future. As a result of the low gravity on Psyche, it seems reasonable to conclude that there are areas of steep terrain and that the topography to radius ratio is 10% minimum (Elkins-Tanton, 2019, p.5), where it is about 1% on the Moon or Mars. This information may have an impact on deciding where to land on the body. In addition, while one can surmise that Psyche's surface layer is metal and silicate, it is unknown if that surface is solid or if metal can form a regolith (Elkins-Tanton, 2019, p.6). If there is a porous regolith on Psyche, that would mean landing there may be similar to landing on the Moon regarding what would lay beneath the spacecraft upon touchdown, even where the force of gravity would remain vastly different. With little currently known regarding what Psyche looks like, many have attempted to model the asteroid. The Shepard model is widely accepted as correct and is being used in the present Psyche mission by NASA. This model classifies Psyche as the largest M-Type asteroid discovered thus far (Shepard, 2021, p.14) and estimates various metrics about the asteroid which are useful in determining future mission specifics. Shepard delves into hypothesized creation theories for Psyche, such as it being "the stripped remnant core of an ancient planetesimal" (Shepard, 2021, p.1), or perhaps an iron or silicate-iron body with a history of ferro-volcanic eruptions, or that it may simply be an amassment of rock from a main body due to recurrent collisions (Shepard, 2021, p.1). The collection of features on Psyche has been cataloged and is listed in **Table B.1**, where it can also be partially visualized in **Figure B.2**, both below (Shepard, 2021, p.12-13).

Table B.1: Listed Features on Psyche Compiled by Shepard

(Shepard, 2021, p.12-13)

Topographical and Albedo Features on Psyche

Feature Name	Lat, Lon (°)	Notes	Confidence	Reference
Alpha (A)	0, 270	Large depression/crater	Likely	F20, this work
Bravo (B)	0, 340→50	Missing mass region, flat side	Almost certain	S17, V18, F20, this work
Charlie (C)	0, 90→150	Missing mass region, flat side, low optical albedo	Almost certain	V18, F20, this work
Delta (D1)	−80, 90	Dynamical depression	Indeterminate	S17
Eros (D2)	−65, 260	Crater (50–75 km)	Almost certain	S17, this work
Foxtrot	+90	Crater (50 km)	Likely	This work
Golf	−45, 15→45	High radar and optical albedos, possible depression	···	This work, V18, F20
Hotel	−45, 120→130	High radar and optical albedo spots, flat topography	···	F20, this work
India	−45, 240→300	Bifurcated radar echoes, elevated radar albedo, high optical albedo	···	V18, F20, this work
Meroe	0→20, 90→120	Crater (80–100 km), low optical albedo	Indeterminate	V18
Panthia	~40, 300	Crater (~90 km), high optical, and high radar albedos	Almost certain	V18, this work
X-ray	0, ~270	Unknown topography, optically dark	Indeterminate	This work

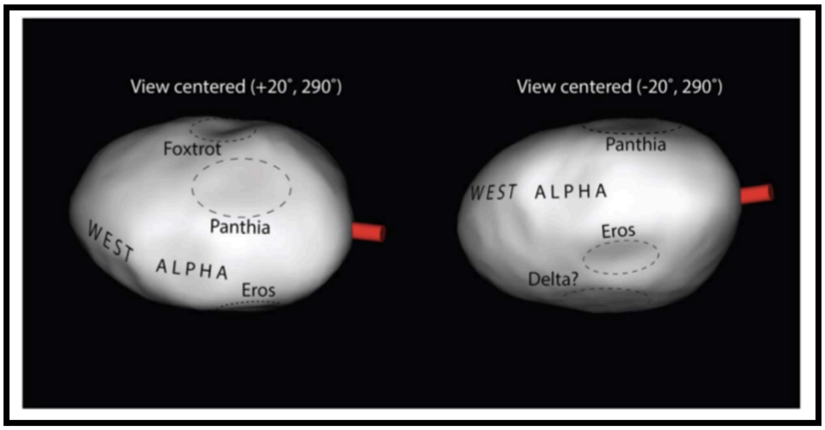


Figure B.2: Visualization of Various Features

(Shepard, 2021, p.12-13)

It is also important to report that the mean radius of Psyche is 113 km, making it smaller than Ceres and Vesta, but larger than Eros, Ryugu, and Itokawa (Zuber, 2022, p.2), dimensions which can be seen below in **Figure B.3**. This information may prove to be useful in selecting design specifics for a future spacecraft considering what was used in the past for voyages to celestial objects of varying sizes. Psyche is also considered a fast-rotating body, as it completes one rotation in a period of 4.2 hours (Shepard, 2021, p.6). These facts are important to remember when attempting to land on such a body, as Psyche's movement and dimensions certainly play a part in the structure and implementation of landing with a potential future spacecraft.

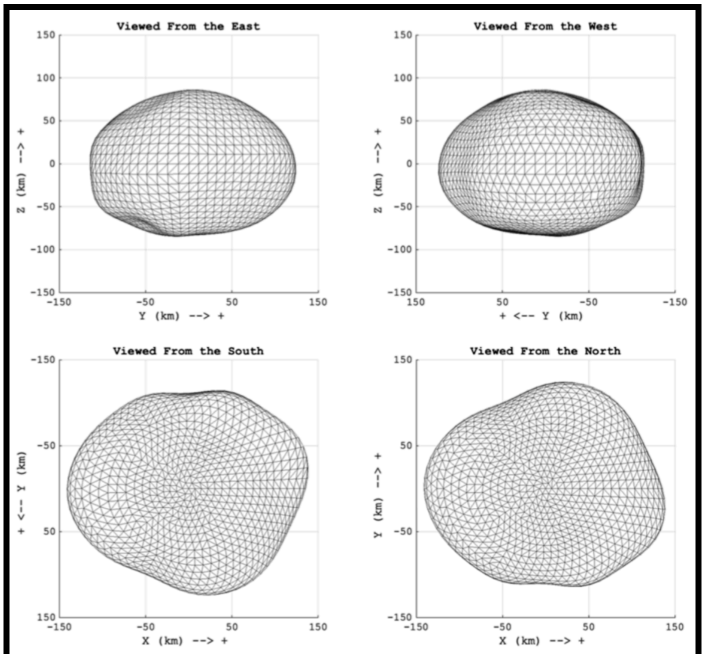


Fig. 2 Shape of Psyche (Shepard et al. 2021) shown from different viewing angles

Figure B.3: Psyche Dimensions
(Zuber, 2022, p.2)

Appendix B.2: Early Design Avenues

To design a landing system for a possible future Psyche landing mission would be to refine the past design choices of successful missions to other astronomical entities. This would include missions to celestial bodies like asteroids Itokawa, Ryugu, and Bennu, comet 67P/Churyumov–Gerasimenko, as well as larger bodies like Earth's Moon, Saturn's moon Titan, Venus, and Mars, among others. Taking inspiration from designs present in these past missions will save time in research as well as money in testing.

Taking from Hayabusa's mission to Itokawa circa 2003, the concept of not permanently landing on an asteroid may prove helpful to other low-gravity pursuits such as Psyche. Further, the sample collection method used by Hayabusa may also be beneficial considering the comparable makeups of Psyche and Itokawa. From Rosetta-Philae, perhaps learning from the misadventures of communication and probe dispatch would be useful in future implementation for quests such as that of Psyche. For the expedition to the near-Earth asteroid Bennu, OSIRIS REx utilized a successful touch-and-go maneuver and may be an alternative option for sample collection.

Deep Impact launched a probe into the surface of the comet Tempel 1, where the orbiter captured photos below the surface and reported back to Earth. The Stardust spacecraft completed a similar task by flying by the same comet and returned to Earth with 72 images and over 10,000 particles of interstellar dust. While these comet missions don't land on the surface of Tempel 1, the idea of interacting with the celestial body and collecting data still may be useful in overall mission objectives.

Appendix B.3: Design Aspects in Communication & Visualization

Sending information back to Earth is not always as near-instantaneous as it was, for example, during the Apollo Missions to Earth's Moon where the delay time in communication is about 2.5 seconds there and back. In the case of Mars, depending on planet positions, the communication delay can reach 20 minutes, and with Psyche orbiting beyond that point, it is important to perhaps include various automated landing devices. Possessing automation in the lander may prove difficult, as has been seen on recent lunar missions in which unmanned landers have been less successful than desired, but in the case of Psyche where the communication delay is large and human intervention is not feasible, it is necessary for landing to be completely automated.

For the Rosetta-Philae mission to 67P, a comet with an almost 30-minute radio signal delay, a system called RSI was utilized. This acronym stands for Radio Science Investigation and it was solar-powered using cells located on the external body of the spacecraft ("Rosetta," 2022). A hurdle for a solar-powered system such as this is that when in the shadows of space, power supplies can run dangerously low; this is something Rosetta faced when in the shadow of 67P. It would be reasonable to consider having a backup power source in cases such as these.

OSIRIS REx combined one high-gain antenna, one medium-gain antenna, and two omnidirectional low-gain antennas in its communication system when it traveled to Bennu. The limitation of this approach is that the "probe [had to be] be shifted in its entirety to aim the high-gain antenna toward Earth" (Shukla, 2023) given that it is externally fixed. The high-gain antenna utilized in this mission for communication can be seen below in **Figure B.4** on the left of the OSIRIS REx spacecraft ("High-Gain Antennas and Solar Arrays Installed on OSIRIS-REx," 2015). While this may not be the most ideal, it certainly would be a viable option for prospective reform and replication.

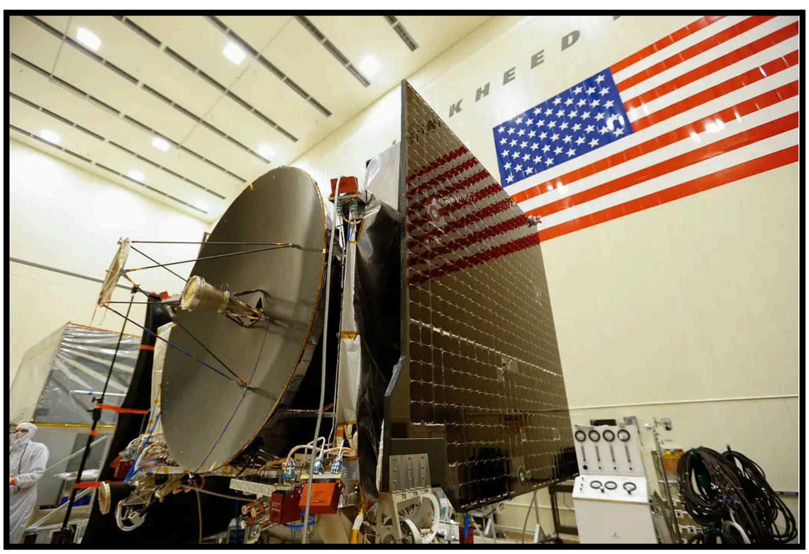


Figure B.4: High-Gain Antenna on OSIRIS REx
("High-Gain Antennas and Solar Arrays Installed on OSIRIS-REx," 2015)

The current Psyche mission utilizes four antennas that send signals through the Deep Space Network (DSN) for communication, but since the purpose of this mission is to collect further information on the asteroid, imaging systems are equally as important. For example, a multispectral imager will be employed to "photograph the surface of the asteroid in different wavelengths of light" ("Psyche Spacecraft - NASA Science," 2023). Additionally, a gamma ray and neutron spectrometer will provide insight into the chemical composition of the exterior and a magnetometer will be utilized to determine the magnetic field of this M-type asteroid ("Psyche Spacecraft - NASA Science," 2023).

Appendix B.4: Design Aspects in Collection Devices & Added Parts

Under the assumption that Psyche has a metal-silicate regolith, it would be useful to implement a horn-style sample collection device such as that which was utilized by Hayabusa on the S-type asteroid Itokawa. In the case of Hayabusa, the horn shot a 5-gram tantalum projectile at 300 m/s at the surface of Itokawa to release debris and promptly collect it ("Hayabusa Sample Collection Methodology," 2023); a visual representation of this device can be seen in **Figure B.5** below. Where Psyche is an M-type asteroid and likely consists of iron metal-silicate, Itokawa is an S-type asteroid meaning it is of siliceous composition which is "metallic iron mixed with iron- and magnesium-silicates" ("Asteroids."), making the two relatively similar enough in constitution so that this collection method remains applicable to the Psyche mission from the Hayabusa mission.

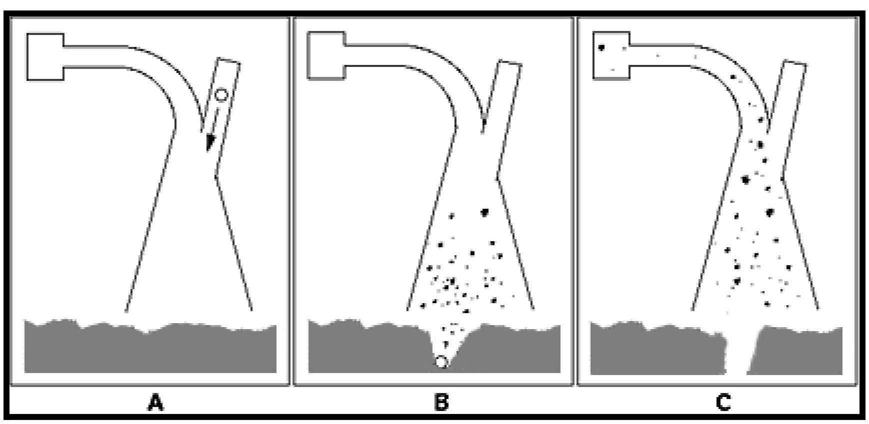


Figure B.5: Hayabusa Sample Collection Horn
("Hayabusa Sample Collection Methodology," 2023)

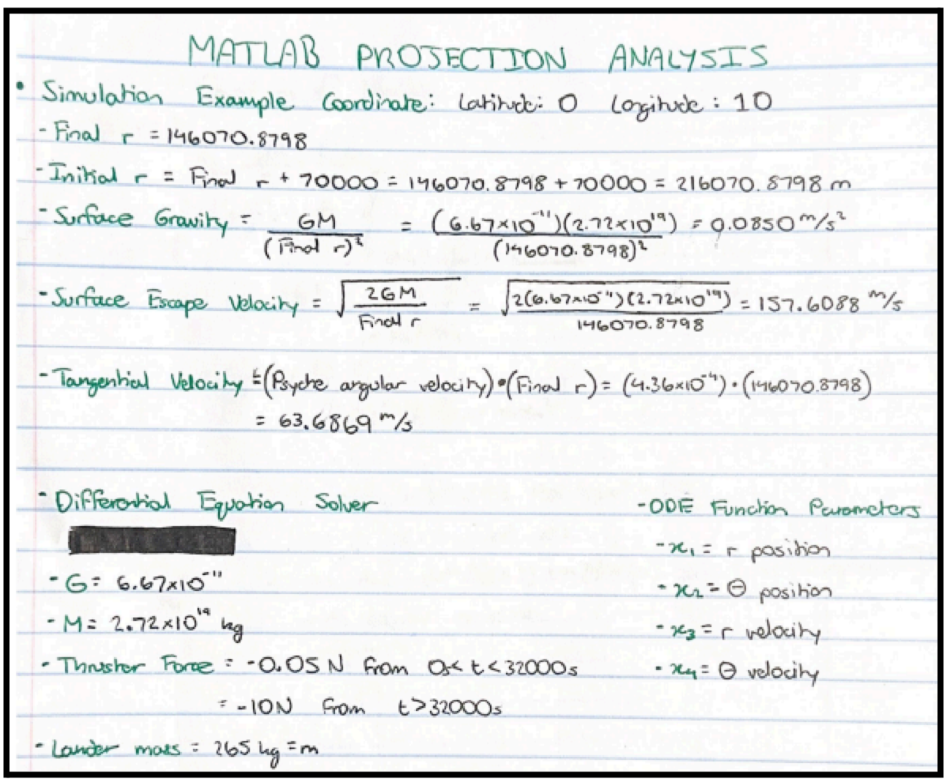
As has been comparably seen in previous NASA missions like OSIRIS REx to the near-Earth B-type asteroid Bennu, collecting material from the surface of a celestial object and bringing it back to Earth is feasible. This route may be beneficial in determining if Psyche truly is a remnant planetesimal core, and further data may be the final step in classifying it as such. In the case of OSIRIS REx, the Touch and Go Sample Acquisition Mechanism (TAGSAM) that was utilized allowed for Bennu's regolith to be easily broken down and collected, while contact pads gathered material from the surface ("OSIRIS-Rex - NASA - NSSDCA - Spacecraft - Details," 2022). In the case that landing on Psyche is not a practicable option, engaging in a touch-and-go maneuver such as that which was used by OSIRIS REx may be a suitable alternative.

Appendix B.5: Alternate Design Inclusions

Other aspects of previous missions may be applicable such as multiple thrusters to account for in-depth maneuverability like on OSIRIS REx, temperature-detecting instruments similar to Rosetta-Philae's MIRO, and perhaps a magnetometer, or multispectral imager from the current Psyche mission. While it may not always be imperative to tackle landing on Psyche with such things, it may be desired to gather information that only these methods' results can provide.

Appendix C: Code

To showcase validation between the Matlab code and the theoretical equations that were used in our analysis, hand calculations were done to show the similarities between the answers derived and the answers displayed in Matlab. **Figure C.1** and **Figure C.2** display the resulting answers to compare to the Matlab code, shown in **Figure C.3**, **Figure C.4**, and **Figure C.5**.



MATLAB PROJECTION ANALYSIS

- Simulation Example Coordinate: Latitude: 0 Longitude: 10
  - Final r = 146070.8798
  - Initial r = Final r + 70000 = 146070.8798 + 70000 = 216070.8798 m
  - Surface Gravity = $\frac{GM}{(\text{Final } r)^2} = \frac{(6.67\times10^{-11})(2.72\times10^{19})}{(146070.8798)^2} = 0.0850\ m/s^2$
  - Surface Escape Velocity = $\sqrt{\frac{2GM}{\text{Final } r}} = \sqrt{\frac{2(6.67\times10^{-11})(2.72\times10^{19})}{146070.8798}} = 157.6088\ m/s$
  - Tangential Velocity = (Psyche angular velocity)•(Final r) = $(4.36\times10^{-4})\cdot(146070.8798)$ = 63.6869 m/s
- Differential Equation Solver
  - [redacted]
  - $G = 6.67\times10^{-11}$
  - $M = 2.72\times10^{19}$ kg
  - Thruster Force = -0.05 N from 0 < t < 32000s
    = -10N from t > 32000s
  - Lander mass = 265 kg = m
- ODE Function Parameters
  - x_1 = r position
  - x_2 = θ position
  - x_3 = r velocity
  - x_4 = θ velocity

Figure C.1: Matlab Hand Calculations

Equation of Motion

① $\bar{F} = \frac{F_m}{m} = r\ddot{\theta} + 2\dot{r}\dot{\theta}$

$$\ddot{\theta} = \frac{\frac{F_m}{m}}{r} - \frac{2\dot{r}\dot{\theta}}{r}$$

② $\frac{GM}{r^2} = \ddot{r} - r\dot{\theta}^2$

$$\ddot{\theta} = \frac{\bar{F}}{r} - \frac{2\dot{r}\dot{\theta}}{r} \quad \begin{cases} \dot{x}_2 = x_4 \\ \dot{x}_4 = \frac{\bar{F}}{x_1} - \frac{2x_3x_4}{x_1} \end{cases}$$

$$\ddot{r} = \frac{GM}{r^2} + r\dot{\theta}^2$$

$$= \frac{\bar{G}}{r^2} + r\dot{\theta}^2 \quad \begin{cases} \dot{x}_1 = x_3 \\ \dot{x}_3 = \frac{-\bar{G}}{x_1^2} + x_1x_4^2 \end{cases}$$

$\therefore$

$$\dot{x}_1 = x_3$$
$$\dot{x}_2 = x_4$$
$$\dot{x}_3 = -\frac{\bar{G}}{x_1^2} + x_1x_4^2$$
$$\dot{x}_4 = \frac{\bar{F}}{x_1} - \frac{2x_3x_4}{x_1}$$

Therefore, in MATLAB, the equation of motion is displayed as:

y=[x3; x4; -(G*M)/(x1^2)+x1*(x4^2); Ft/(m*x1)-(2*x3*x4)/x1];

with respect to time

Figure C.2: Matlab Equation of Motion

```
prompt = "What is the Longtitudinal coordinate of the landing site? ";
Long = input(prompt); % x
Lat= 0 ;     % y
% Z coordinate is always 0 due to every point being on the equator

if Long == 10
    rf = 146070.8798;
    ri = rf + 70000;
    g_Surface = (G*M)/((rf)^2);          % Gravity on the Surface
    Ve = sqrt((2*G*M)/(rf));             % Surface Escape Velocity
    Vr = theta_dot_psyche*rf;            % Tangential Velocity of Psyche Location

elseif Long == 220
    rf = 123183.413;
    ri = rf + 70000;
    g_Surface = (G*M)/((rf)^2);          % Gravity on the Surface
    Ve = sqrt((2*G*M)/(rf));             % Surface Escape Velocity
    Vr = theta_dot_psyche*rf;            % Tangential Velocity of Psyche Location

 elseif Long == 130
    rf = 124185.4403;
    ri = rf + 70000;
    g_Surface = (G*M)/((rf)^2);          % Gravity on the Surface
    Ve = sqrt((2*G*M)/(rf));             % Surface Escape Velocity
    Vr = theta_dot_psyche*rf;            % Tangential Velocity of Psyche Location
```

Figure C.3: Matlab Input Code

```
tspan = [0 33380];% time duration for which you want to simulate the system
x0 = [r -0.3 0 5.3101E-4];% initial conditions [ r, theta, r_dot, theta_dot(Angular Velo of lander)] 0.0004363  5.3101E-4

options = odeset('RelTol',1e-12, 'AbsTol',1e-12);
[t,y] = ode45(@ODE,tspan,x0,options);%functin to solve diffrential equation.
```

Figure C.4: Matlab Initializing the ODE

```
G = 6.67*10^-11;          % Gravitational constant
M = 2.72*10^19;           % Psyche Mass (kg)
Ft = -0.05;               % Force of Thrusters
m = 265;                  % mass of lander (kg)

                          % The fuel is only .5% of the total weight
                          % The fuel is less than 4% of the total weight
if t > 31960
    Ft = -9.4;
end

%equation of motion
y = [x3; x4; -(G*M)/(x1^2) + x1*(x4^2); Ft/(m*x1) - (2*x3*x4)/x1];
end
```

Figure C.5: Matlab Equation of Motion ODE Output

Table C.1: Matlab Overall Results

Longitude	Location	Radius (m)	tspan (s)	theta	Low Ft (N)	High Ft Time (s)	High Ft (N)	Surface Gravity (m/s^2)	Ve (m/s)	Rf (m)	Vf (m/s)	Theta dot final (rad/s)
10	Delta	146071	33380	-0.3	-0.05	31960	-9.4	0.085	157.6088	145945	-39.88	0.000434
130	Charlie	124185	35460	0.75	-0.05	33690	-10.2	0.1176	170.9334	124199	-70.81	0.000435
180	Echo	147000	35400	1.4	-0.05	34030	-9.5	0.084	157.11	147013	-38.56	0.000433
220	Alpha	123183	35460	-4.3	-0.05	33670	-10.2	0.1196	171.6273	122786	-72.69	0.000438
300	Bravo	120751	35460	-2.6	-0.05	33650	-10.4	0.1244	173.3476	120647	-76.09	0.000435

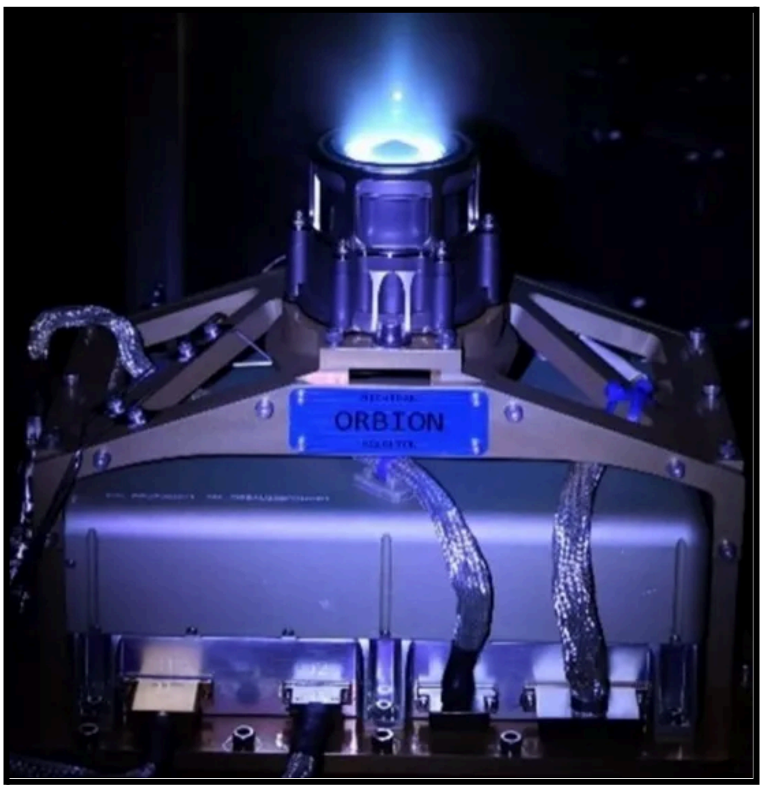


Figure C.6: Low Thrust Engine Employed
(“4.0 in-Space Propulsion.” 2024)

Characteristics	
Thrust Range	7.9 ... 24.6 N
Supply Pressure Range	5.5 bar - 24 bar
Nominal Mass Flow Range	3.2 g/s ... 10.4 g/s
Nominal Specific Impulse Range	222 s ... 230 s
Minimum Impulse Bit Range	0.238 ... 0.685 Ns
Nozzle area ratio	60
Mass	≈ 650 g (with 1.5 m flying leads)
Propellant	Monopropellant grade Hydrazine (N_2H_4)
Environmental Loads	16.2 grms
Qualification	
Total Impulse	> 517,000 Ns
Total number of pulses	> 93100
Total hydrazine throughput	> 290 kg
Total operating time	10.5 h
Logest steady state burn	1.5 h
Number of cold starts < 20°C	36
Number of cold starts at 0°C	12

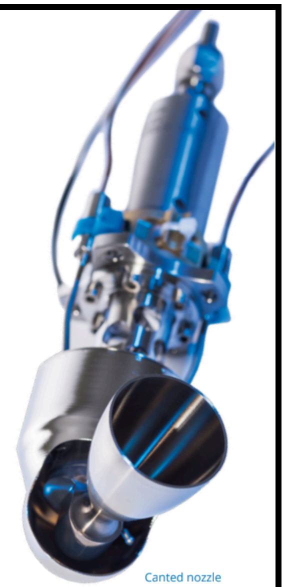


Figure C.7: High Thrust Engine Employed

("Hydrazine Thrusters." 2024)

Appendix D: Team Roles

To begin a project as a team is to decidedly work dynamically with one another. The team that worked on this report and corresponding aspects of the project to land on (16) Psyche sometime in the future includes members Catherine Schenone, Carter Beck, Atharva Burande, Enido Shyti, and Noah Benson. The roles integrated within this report were originally divided into research and mathematics sections. Catherine Schenone and Noah Benson were responsible for research while Carter Beck, Enido Shyti, and Atharva Burande were responsible for mathematics. The specific breakdown of this dynamic can be seen below separated per the sections listed in the table of contents.

Section	Author(s)
Table of Contents	*C. Schenone*
Acknowledgments	*C. Schenone*
Nomenclature	*A. Burande, E. Shyti, C. Schenone*
Introduction to the Problem	*C. Schenone*
Identification of Needs	*C. Schenone*
Problem Constraints	*C. Schenone*
Solution Research and Benchmarking	*C. Schenone*
Problem and Solution Impact on Public Welfare/the Environment/Sustainability	*C. Schenone*
Concise Problem Definition and Deliverables	*C. Schenone*
Initial and Contingency Plans	*C. Schenone*
Analyses	*C. Beck, A. Burande, E. Shyti, C. Schenone*
Code Generation	*C. Beck, A. Burande, E. Shyti, C. Schenone*
Concept Designs, Results, and Justification	*C. Beck, C. Schenone*
Conclusions and Recommendations	*C. Schenone*
Appendix A: Initial Information	*C. Schenone*
Appendix B: Miscellaneous Data	*C. Schenone*
Appendix B.1: Preliminary Research	*C. Schenone*
Appendix B.2: Early Design Avenues	*N. Benson, C. Schenone*
Appendix B.3: Design Aspects in Communication & Visualization	*C. Schenone*
Appendix B.4: Design Aspects in Collection Devices & Added Parts	*C. Schenone*
Appendix B.5: Alternate Design Inclusions	*C. Schenone*
Appendix C: Code	*A.Burande,C. Beck, C. Schenone*
Appendix D: Team Roles	*C. Schenone*
Works Cited	*C. Schenone*

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