Development of the Psyche Mission for NASA's Discovery Program

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Abstract: In January 2017, the proposed mission *Psyche: Journey to a Metal World*, led by principal investigator Dr. Lindy Elkins-Tanton of Arizona State University (ASU), was selected for implementation as part of NASA's Discovery Program. The planned Psyche mission is enabled by electric propulsion and would use SPT-140 Hall thrusters to rendezvous and orbit the largest metal asteroid in the solar system. The spacecraft requires no chemical propulsion and, when launched in 2022, would be the first mission to use Hall thrusters beyond lunar orbit. This paper describes the ongoing development of the Psyche mission concept and describes how Psyche would use commercially provided solar power and electric propulsion to meet its mission's science requirements. It describes the mission's scientific objectives and low thrust mission trajectory, the spacecraft architecture, including its power and propulsion systems, and the all-electric attitude control strategy that allows Psyche to fly without the use of chemical propulsion. Together, these elements provide a robust baseline design that maximizes heritage, leverages the strongest experience bases within the partner organizations, and minimizes risk across the design; providing a firm basis for implementation of the Psyche mission.

I. Introduction

SINCE 1992, NASA's Principal Investigator (PI)-led Discovery Program has amassed a compelling list of mission successes: NEAR, Mars Pathfinder, Lunar Prospector, Genesis, Deep Impact, Stardust, Kepler, GRAIL, MESSENGER, and most recently Dawn's mission to Vesta and Ceres.[1] The dramatic success that Dawn achieved

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by completing its primary objectives at Vesta in 2012 and at Ceres in 2016 demonstrates the unique value that solar electric propulsion (SEP) brings to NASA by enabling planetary science missions that are impractical or impossible to conduct using other methods.[2] More broadly, NASA's Discovery Program has amply demonstrated the benefits of cost capped, competitively awarded science missions for space exploration.

In January 2017, the proposed mission *Psyche: Journey to a Metal World*, led by PI Dr. Lindy Elkins-Tanton of Arizona State University (ASU), was selected for implementation as part of NASA's Discovery exploration program. The Psyche mission is enabled by electric propulsion and would use SPT-140 Hall thrusters to rendezvous and orbit (16) Psyche,[§§§] the largest metal asteroid in the solar system. The Psyche spacecraft requires no chemical propulsion and, when launched in 2022, would be the first mission to use Hall thrusters beyond lunar orbit. It would also carry the most xenon ever flown on a single NASA spacecraft.

This paper describes the ongoing development of the Psyche mission concept and describes how Psyche would use commercially provided solar power and electric propulsion systems to address the unique challenges posed by this mission. It describes the mission's scientific objectives and low thrust mission trajectory, describes the spacecraft's architecture, including its power and propulsion systems, and discusses the all-electric attitude control strategy that allows Psyche to fly without the use of chemical propulsion. Together, these elements provide a robust design architecture that maximizes heritage, leverages the strongest experience bases within the partner organizations, and minimizes risk across the baseline design; providing a firm basis for implementation of the Psyche mission.

II. Project Overview

In 2014, a two-step competition was initiated to select the next missions in NASA's Discovery planetary exploration program. In January 2017, two out of 27 mission concepts initially submitted into competition were selected for implementation. One mission, *Lucy*, would use a combination of chemical propulsion and gravity assists to conduct flybys of six Trojan asteroids. The other, *Psyche*, would use electric propulsion and a Mars gravity assist to rendezvous with and orbit the largest metal asteroid in the solar system. Lucy was selected to launch in 2021, and Psyche was selected to launch in 2023, but the flexibility afforded by its electric propulsion system has enabled the development of a trajectory that would launch Psyche a year earlier, in August 2022. The new trajectory is highly optimal and would effectively accelerate the arrival date at the asteroid by four years, from 2030 to 2026.[3]

The Discovery Program uses a competitive selection process that emphasizes scientific merit and challenges mission architects to find all sources of potential cost growth and technical uncertainty (i.e. risks), and effectively mitigate them to produce a simple, low-risk, mission concept that can be implemented within a strict mission cost cap. The need for low-risk leads naturally to the use of solar power and electric propulsion systems with solid *system level* heritage and high TRL (technology readiness level).[4] As described previously, Psyche's design addresses these needs with a unique adaptation of commercial power and electric propulsion systems provided by Space Systems/Loral (SSL).[5] The mission architecture takes full advantage of the capability provided by electric propulsion in its mission design, with the flexibility to launch in multiple years and the orbital maneuverability and momentum management capability for attitude control needed to support all required science observations at Psyche.

This paper describes the ongoing development of the Psyche mission concept, including the development of a new 2022 launch trajectory. Section III provides an overview of the planned Psyche mission, including its science objectives and trajectory. Section IV describes the overall spacecraft architecture, including the power and propulsion system. It also describes the unique strategy used to conduct all-electric momentum management in deep space, which in turn enables Psyche to fly without the use of chemical propulsion.

III. Mission Concept Overview

A. Science Objectives and Payload

The science target for this mission is the large asteroid Psyche (~279 x 232 x 189 km) that orbits the Sun at ~3 AU.[6] Psyche is a world unlike any other in the solar system. It is composed almost entirely of metal, larger than any other metal body, and it is a mystery: a world full of questions. How was Psyche created? What does a metal world even look like? What is the connection between it and the other planets, including our own? This mission

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[§§§] The IAU designation is (16) Psyche. For clarity, we will use Psyche throughout this paper.

concept would explore these mysteries, and in doing so answer fundamental questions about the creation of the solar system.

Psyche's metal composition was hinted at by some earlier studies that showed it has anomalously high density,[7] but its largely metal bulk composition was confirmed by measurements of a radar albedo of 0.42 and thermal inertia of ~120 J m^{-2} $S^{-0.5}$ K^{-1} (the rocky asteroids Ceres, Pallas, Vesta, Lutetia all have thermal inertia between 5 to 30 J m^{-2} $S^{-0.5}$ K^{-1}).[8,9] While Psyche's bulk appears to be metal, its surface appears to have small areas that are rocky. A 0.9 µm absorption feature suggests a few percent of its surface is high-magnesian orthopyroxene,[10] and new results indicate hydrous features, likely hydrated silicates from chondritic impactors.[11]

Meteorites indicate that solids in the early solar system accreted into bodies called planetesimals, tens to hundreds of kilometers in diameter, within a few hundred thousand years of the beginning of the solar system.[12] Meteorites also show that these planetesimals heated sufficiently that their metal components melted and sank to the interiors to form a core, while the rocky components remained on the outside of the differentiated body.

Models show that among the accretionary collisions early in the solar system, some destructive "hit and run" impacts stripped the silicate mantle from differentiated bodies.[13] This is the leading hypothesis for Psyche's formation: it is a bare planetesimal core. Models also show that four to eight hit-and-run collisions are needed to strip the rocky material away to reveal a metal world like Psyche, and that such an occurrence is rare. If our observations indicate that it is not a core, Psyche may instead be highly reduced, primordial metal-rich materials that accreted closer to the Sun. The origin of the metal world Psyche, therefore, is of great interest: will it be the first, and only, metal core that humankind will ever see? Or will it confirm the existence of highly reduced, primordial materials that have been hypothesized but never detected?

Psyche's mission of exploration is defined by five scientific objectives:

1) Determine whether Psyche is a core, or if it is unmelted material.
2) Determine the relative ages of regions of its surface.
3) Determine whether small metal bodies incorporate the same light elements as are expected in the Earth's high-pressure core.
4) Determine whether Psyche was formed under conditions more oxidizing or more reducing than Earth's core.
5) Characterize Psyche's topography and impact crater morphology.

The Psyche mission would meet these objectives by orbiting the asteroid and examining it with a scientific payload consisting of three remote sensing instruments and with radio science conducted using its X-band communication system, as shown in Table 1.

Table 1: Psyche's Science Payload Consists of Three High Heritage Instruments and Radio Science

Instrument	Flight Heritage	Key Measurements
Multi-spectral Imager	Curiosity Rover Mastcam	Surface geology, composition, and topographic
Gamma Ray and Neutron Spectrometer	MESSENGER	Key elemental composition (i.e. Fe, Ni, Si, and K) Surface compositional heterogeneity
Fluxgate Magnetometer	Magnetospheric Multiscale Mission (MMS) and Insight	Magnetic field characterization
Radio Science (X-band)	Multiple	Gravity field mapping

Two block-redundant multispectral imagers provided by instrument lead Dr. Jim Bell at Arizona State University (ASU) working with Malin Space Science Systems (MSSS) would image the asteroid with seven color filters and one clear filter. A Gamma Ray and Neutron spectrometer provided by instrument lead Dr. David Lawrence at the Applied Physics Laboratory (APL) would measure surface elemental composition. Dual fluxgate magnetometers provided by investigation lead Dr. Ben Weiss at MIT and development lead Dr. Chris Russell at UCLA, would operate in a gradiometer configuration to characterize Psyche's magnetic field. The spacecraft's X-band telecommunications system would conduct radio science for an investigation led by Dr. Maria Zuber at MIT that will map Psyche's gravity field using the spacecraft's X-band telecommunications system.

In addition to the science payload, Psyche also includes an additional technology demonstration payload: a deep space optical communications payload (DSOC) that would conduct high-rate communications using lasers between the spacecraft and ground stations on Earth in support of future deep space missions.

B. Mission Architecture: Cruise Trajectory

Accomplishing the project's science objectives requires traveling to Psyche and orbiting the asteroid for a period of 21 months. In order to reduce operations costs and receive science data as early as possible, it is desirable to minimize the trip time from Earth to Psyche. Therefore, the fundamental objective of the mission design effort is to deliver the necessary spacecraft mass (including margins) to the asteroid Psyche as quickly as possible. The constraints on the trajectory imposed in the Discovery 2014 Announcement of Opportunity (AO) included a maximum allowed launch vehicle performance capability (which corresponded to an Atlas V 411 launched from Cape Canaveral, Florida) and a launch readiness date prior to December 31, 2021.[1] (The AO guidelines allowed the use of higher performing launch vehicles, but at an additional cost to the project). To enable the selection of multiple winners with staggered launch dates, the AO also asked teams to identify an alternative launch period in 2023. The final Psyche proposal included launch options in both 2021 and 2023, and ultimately NASA selected the 2023 launch opportunity.

Early studies showed that the amount of chemical propellant required to reach and orbit Psyche within a reasonable time is prohibitively high. This led naturally to the use of electric propulsion and low thrust trajectories for the mission. Prior to the first down selection in September 2015 ("Step 1"), Psyche's low thrust trajectory design work was conducted using MALTO.[14] From that point onward ("Step 2"), all trajectory design work was conducted with the trajectory optimization program Mystic.[15] Mystic is a high-fidelity optimization tool that was used for all mission design and maneuver design work for the Dawn Mission to Vesta and Ceres. Mystic has assisted other flight projects including the Cassini and Artemis missions. Mystic uses a second order optimal control algorithm called Static-Dynamic Optimal Control (SDC)[16] based on Bellman's principal of optimality. SDC achieves both the necessary and sufficient conditions.

A further constraint on the trajectory was to have the spacecraft arrive during optimal lighting conditions at Psyche. Optimal lighting allows near complete Sun lit visibility of Psyche during early proximity operations. Arriving at sub-optimal lighting times may require a more drawn out mission to achieve all objectives. Both arriving at an optimal lighting time and reducing the interplanetary cruise time were the important objectives, as both reduce the overall duration and cost of the prime mission.

The flexibility provided by electric propulsion was critical to navigating changing requirements through the development process. In Step 1, the propellant for the interplanetary cruise was limited to 935 kg of xenon (deterministic). The proposed launch date for Psyche was late summer/fall of 2020, the flight time was 5.3 years, and Psyche capture was in January of 2026. The trajectory used a single Mars gravity assist in May 2023 and delivered 1790 kg total mass to Psyche capture.

In Step 2, because of a slip in the selection date, it became clear that the project would require a launch opportunity in 2021 and a second opportunity in 2023. The xenon propellant allocated to interplanetary cruise was also reduced from 935 kg to 915 kg. In response, a detailed analysis of all feasible trajectories in the years 2021 through 2024 was completed. Other constraints placed on the trajectory search included a 90% duty cycle during cruise phase, a 50% duty cycle during approach to Psyche (the final 100 days before science orbit injection), a post launch forced coast of at least 90 days, pre-Mars and pre-Earth flyby forced coasts of at least 60 days, and post-Earth and post-Mars flyby forced coasting of at least 15 days. For both the 2021 and 2023 opportunities, the total power generated by the solar arrays was 17 kW beginning of life power at a solar distance of 1 Astronomical Unit (AU) (equivalent to four panels on each wing) and end of life low-intensity low-light (LILT) solar cell performance was assumed at all times. A power of 780 watts was allocated to spacecraft bus throughout the trajectory.

It was found that Mars flybys alone either did not provide adequate mass performance or resulted in long flight times in these two candidate launch years. The 2021 launch opportunity discovered by Mystic utilized both an Earth and Mars flyby. The flybys of both Earth and Mars are constrained to a minimum altitude of 500 km for planetary protection. Table 2 provides the characteristics of the proposed 2021 mission and the originally proposed 2020 mission for comparison.

Table 2: Comparison of 2020 (Step 1) and 2021 (Step 2) Launch Opportunities

	2021 Opportunity E-E-M-P (Earth-Earth-Mars-Psyche)	**2020 Opportunity E-M-P (Earth-Mars-Psyche)**
Launch Period Start Date (approximate)	August 1, 2021	November 21, 2020
Launch C_3	14.8 km^2/s^2	16.8 km^2/s^2
Declination Angle (DLA)	-22.8 to -28.5 deg	28.5 deg
Time of Flight, Psyche Capture	4.4 years, January 26, 2026	5.3 years, January 1, 2026
Earth Gravity Assist (altitude, date)	14,282 – 25,074 km August 3, 2022	None
Mars Gravity Assist (altitude, date)	500 km, May 7, 2023	500 km, May 10, 2023
Cruise propellant mass (deterministic)	915 kg	935 kg
Delivered mass (across launch period)	1,946 kg	1,790 kg
Minimum Heliocentric Distance	0.89 AU	1.0 AU
Bus Power Consumption	780 watts	590 watts
Solar Array (EOL, 1 AU equivalent)	15,979 watts (four panels)	15,780 watts (four panels)

The 2021 opportunity identified in Step 2 is superior in all regards to 2020 opportunity used in Step 1 except for a new thermal requirement to operate at solar distances as low as 0.89 AU associated with the Earth gravity assist trajectory. Both opportunities arrive at approximately the same time and with optimal lighting conditions. The shorter flight time in 2021 reduces cost and risk. A similar Earth-Earth-Mars-Psyche trajectory exists in 2023 and served as the alternative opportunity. The 2023 opportunity has similar characteristics in all regards to the 2021 opportunity except it does not arrive at the start of optimal lighting conditions. As a result, the flight time was extended to include the next optimal lighting period. Table 3 provides characteristics of the proposed 2023 opportunity.

Table 3: 2023 (Step 2 alternative) Launch Opportunity

	2023 Opportunity E-E-M-P (Earth-Earth-Mars-Psyche)
Launch Period Start Date (approximate)	October 9, 2023
Launch C_3	12.5 km^2/s^2
Declination Angle (DLA)	+8.4 to +19.4 deg
Time of Flight, Psyche Capture	6.9 years, August 26, 2030
Earth Gravity Assist (altitude, date)	7,500 – 10,700 km, October 16, 2024
Mars Gravity Assist (altitude, date)	500 km, May 5, 2025
Cruise propellant mass (deterministic)	915 kg
Delivered mass (across launch period)	2,100 kg
Minimum Heliocentric Distance	0.89 AU
Bus Power Consumption	780 watts
Solar Array (EOL, 1 AU equivalent)	15,973 watts (four panels)

At the end of Step 2, NASA selected Psyche for launch during the 2023 launch opportunity. After selection, the project was asked to investigate launches up to one year earlier (second half of 2022 being the most desirable) and was allowed to consider higher performance launch vehicles and larger solar arrays, in an attempt to shorten the total mission time. It was found that increased solar array power makes a short Earth – Mars – Psyche trajectory possible in 2022. A higher performing launch vehicle provided less benefit. The 2022 opportunity is similar to the 2021 opportunity, but without the Earth Gravity assist. This trajectory fails to deliver adequate mass to Psyche with the 17 kW four-panel solar array, but with a five-panel array providing approximately 20 kW 1 AU BOL power, it delivers more mass than the 2021 opportunity. The 2022 opportunity has the added advantage that it does not need to travel to heliocentric distances below 1 AU. Despite launching a year later than the proposed 2021 launch, it arrives at the same time (January 2026) – during optimal lighting conditions at Psyche. Table 4 provides the characteristics of the proposed 2022 mission as well as an alternate 2024 option.

Table 4: 2022 and 2024 (Phase B) Launch Opportunities

	2022 Opportunity E-M-P (Earth-Mars-Psyche)	**2024 Opportunity E-M-P (Earth-Mars-Psyche)**
Launch Period Start Date (approximate)	August 6, 2022	September 18, 2024
Launch C3	14.5 km^2/s^2	13.6 km^2/s^2
Declination Angle (DLA)	+4.4 to -8.1 deg	+6 to -3 deg
Time of Flight, Psyche Capture	3.6 years, January 2026	5.1 years, December 2029
Earth Gravity Assist	Not Applicable	Not Applicable
Mars Gravity Assist	500 km, May 2023	500 to 973 km, July 2025
Cruise propellant mass (deterministic)	915 kg	915 kg
Delivered mass (across launch period)	1,965 kg	2,020 kg
Minimum Heliocentric Distance	1.0 AU	1.0 AU
Bus Power Consumption	780 watts	780 watts
Solar Array (EOL, 1 AU equivalent)	19,970 watts (five panels)	19,970 watts (five panels)

In May 2017, the 2022 launch opportunity was adopted as the baseline trajectory for the project. This option is significantly superior to both the 2021 and 2023 opportunities. The launch declination is relatively benign, the flight time is much shorter, and no excursion below 1 AU from the Sun is necessary. A similar, though longer, flight time Earth – Mars - Psyche opportunity exists in 2024. The 2024 opportunity has a longer flight time and arrives in sub-optimal lighting conditions. Figure 1 illustrates the lighting conditions at Psyche and flight times for the launch opportunities discussed here. Ideal arrival times are at the beginning of each light period. Figure 2 illustrates the current primary launch period mission.

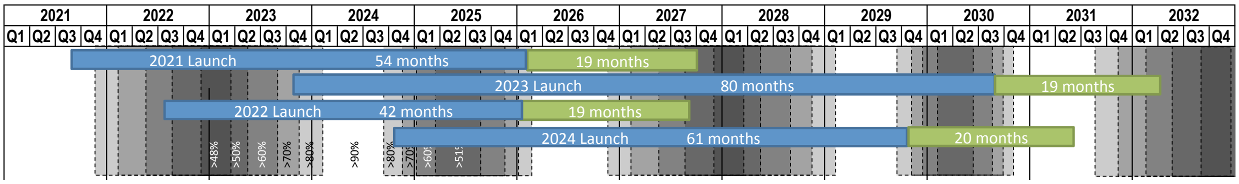


Figure 1: Percent of Psyche illuminated as a function of date. Ideal arrival dates are near the beginning of each white area. The 2022 trajectory timelines is now the baseline mission.

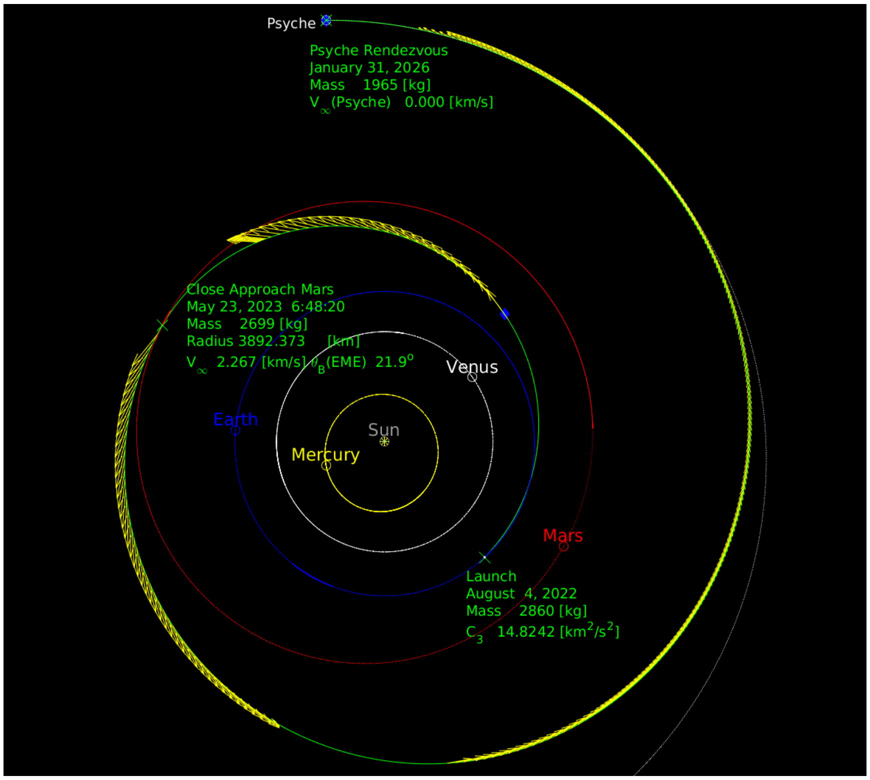


Figure 2: Example 2022 launch trajectory plotted as a green line. Thrust acceleration is indicated by the yellow vectors, arcs without vectors are either forced to coast or coasting is optimal.

C. Mission Architecture: Orbital Operations at Psyche

Once the spacecraft enters orbit at Psyche, it enters a series of progressively lower science orbits that improve data quality as gravity field knowledge allows navigation to lower and lower altitudes. Since Psyche is a previously unvisited body, its physical characteristics and orbital parameters (e.g., shape, density variations, pole orientation, and rotation rate) are highly uncertain and will not be accurately determined until arrival. Therefore, the orbit design has to be robust to the physical uncertainties of Psyche while satisfying the science requirements and spacecraft safety constraints. As demonstrated by Dawn at Vesta and Ceres, a gradual descent to an unmapped body is preferable because this strategy allows progressive and methodical characterization of the Psyche shape and gravity field at each orbit altitude so that adequate gravity knowledge is obtained to design subsequent lower orbits and associated transfers.[17,18] As a result, Psyche would perform orbital science operations for 21 months from four progressively lower science orbits (shown in Figure 3). Orbits A, B, and C are stable, sun-synchronous, polar orbits with ground-track repeat cycles and spacing that allow sufficient coverage from their respective altitudes. Orbit A is sufficiently far from Psyche for gravity perturbations to be negligible, but still close enough to detect the magnetic field and obtain a reliable model of the gravity field for planning the lower orbits. Orbit B enjoys the best lighting conditions to produce global topographic maps of Psyche. Orbit C is the prime orbit for gravity science and is the lowest stable polar orbit above the 1:1 Psyche resonance that is safe to transfer to. Orbit D, also stable, is inclined, retrograde, and at less than one body-radius altitude to produce satisfying GRNS measurements. The overall timeline includes a time margin of 85 days that can be allocated at any point throughout the proximity operations.

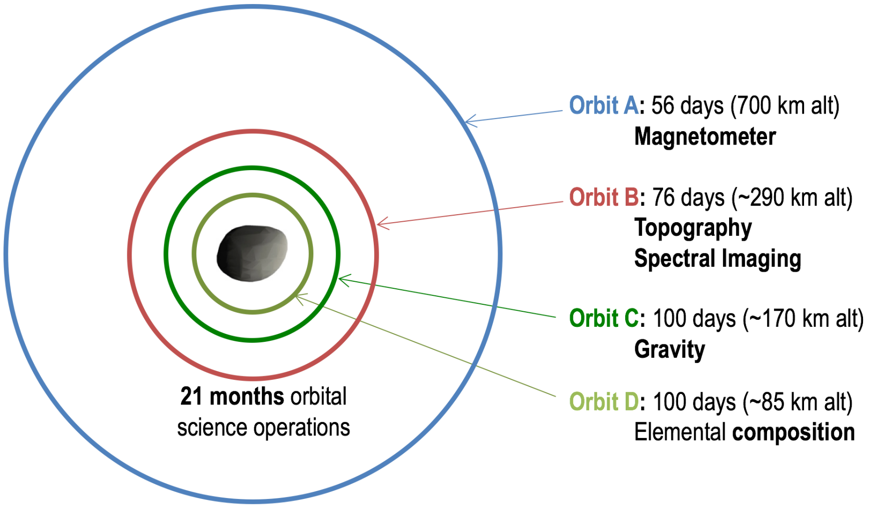


Figure 3: Psyche's progressive science orbits improve data quality as gravity field knowledge allows navigating to lower altitudes

The driving challenge is assuring orbit stability for both low-altitude orbits and transfers between orbits around a large, unexplored asteroid with irregular shape and complex dynamical environment. For reasons of safety and practicality, it is necessary to consider highly stable orbits only to minimize the influence of uncertainties in the gravity field and spacecraft states (from imperfect delivery, navigation errors, and unpredictable momentum desaturation impulses) and reduce the number of required orbit maintenance maneuvers. If an event occurs that puts the spacecraft in safe mode with a loss of control, an impact or an escape of the spacecraft would be unlikely to occur on a stable orbit. Following the approach successfully used on Dawn,[19] a rigorous orbit selection process is applied by exploring numerically the dynamical environment around Psyche. Over 1,000 different candidate gravity models were generated using a 3-sigma Gaussian distribution on the gravity coefficients of the reference model to understand the orbit design space and find stable regions as a function of orbit radius and inclination. Stable regions in the orbit parameter space (radius, inclination, and longitude of ascending node) were found from simulations over a wide range of initial conditions. The stable orbits are shown in Figure 4 and have semi-major axis, eccentricity, and inclination that vary only gradually and within acceptable ranges for at least 28 days without operator intervention. This approach accommodates Dawn's fault-tolerance criterion for orbit stability that is adopted for Psyche. Overall, the location of the stability regions in Figure 4 confirms that inclined, retrograde orbits can be stable close to Psyche, while it is possible to find stable, polar orbits above the 1:1 resonance. These results are in good agreement with general stability investigations around asteroids.[20] Moreover, the safe and effective use of inclined, retrograde, close orbits was demonstrated by the NEAR mission.[21]

More time is spent in Orbit C than required for science to avoid excessive eclipse durations in Orbit D. In fact, for non-polar, retrograde orbits, the orbital plane is precessing rapidly and it is not possible to keep the beta angle (the angle between the orbital plane of the spacecraft and the vector to the sun) constant. It follows that the spacecraft can go into shadow. Psyche has a high axial tilt and is therefore lying down nearly sideways with respect to its orbit around the Sun. As a result of this particular pole orientation, the maximum eclipse duration the spacecraft can experience at a given inclination varies significantly depending on the date. Figure 5 shows the maximum eclipse duration as a function of time for 120-deg, 145-deg and 160-deg orbit inclinations. As Psyche moves away from solstice, it can be seen that the maximum eclipse duration decreases for near- equatorial orbits (145-deg and 160-deg inclination), until no eclipse occurs around equinox. A 160-deg inclination is selected for Orbit D because it offers eclipse durations of less than 30 min as early as April 2027. The spacecraft can tolerate eclipses as long as 65 minutes in duration.

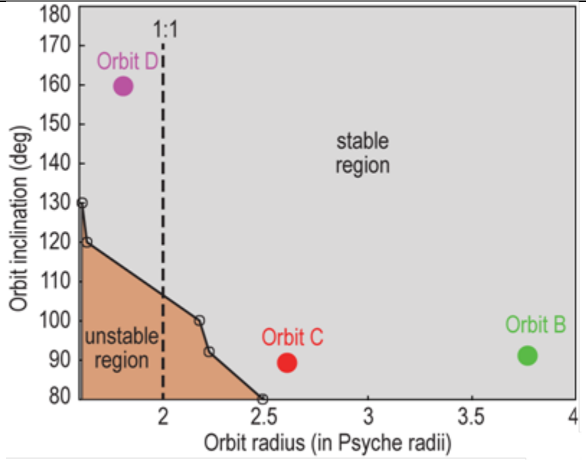


Figure 4: Science orbits produced from a comprehensive numerical survey (brown: unstable; grey: stable).

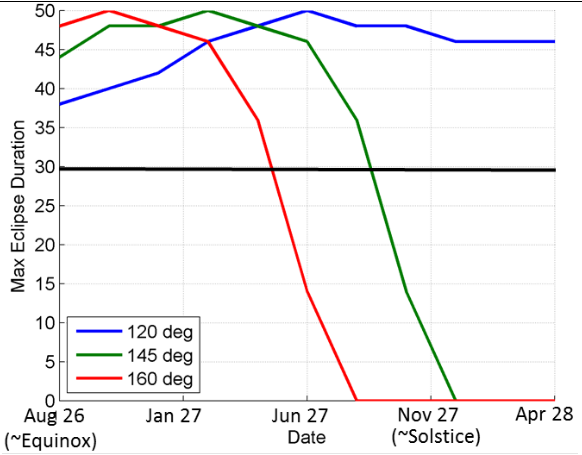


Figure 5: Maximum eclipse duration vs Date at Orbit D for different inclinations

Each orbital transfer was computed using Mystic as a fixed-time trajectory optimization problem with a minimum-propellant cost function. For each transfer, Mystic was given the 6-state targets of the corresponding science orbit at the time of orbit insertion. When no inclination change was required, Mystic was provided with an initial guess consisting of a simple anti-velocity thrust profile to spiral in toward the targeted radius. For large inclination changes, the Lyapunov feedback control Q-law was used as initial guess.[22] An estimate of the flight time for each transfer was obtained using a lower-fidelity, averaging optimization algorithm expressed in nonsingular equinoctial mean elements.[23] All science orbits and associated orbital transfers are shown in Figure 6. Time histories of orbit radius, inclination and beta angle throughout the science orbits and transfers are shown in Figure 7, Figure 8 and Figure 9. Note that the unallocated time margin and approach durations are not included in these plots. A 50% average SEP duty cycle is assumed to enable robust orbit transfers (similar to how Dawn flew at Vesta and Ceres).[17,18] This margin accommodates coast arcs for tracking and communications, and short burn arcs to "walk back" from measured perturbations. Like Dawn, the transfers can also accommodate 28 days of missed thrust without violating any flight system requirements.

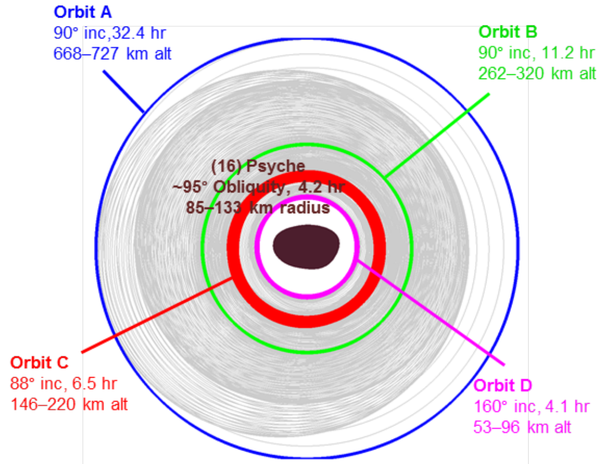


Figure 6: Science orbits and corresponding SEP transfers (projected on instantaneous orbital plane).

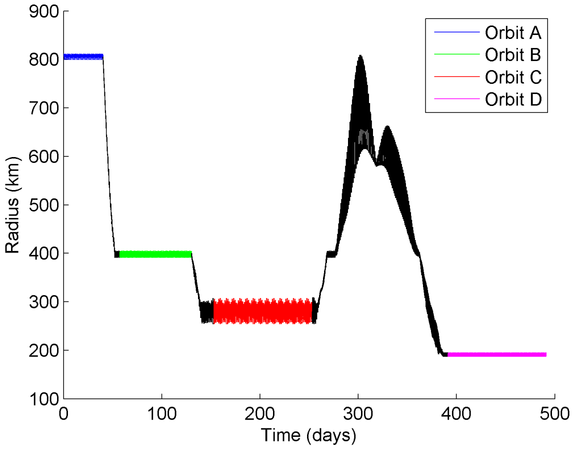


Figure 7: Time history of orbital radius for proximity operations at Psyche.

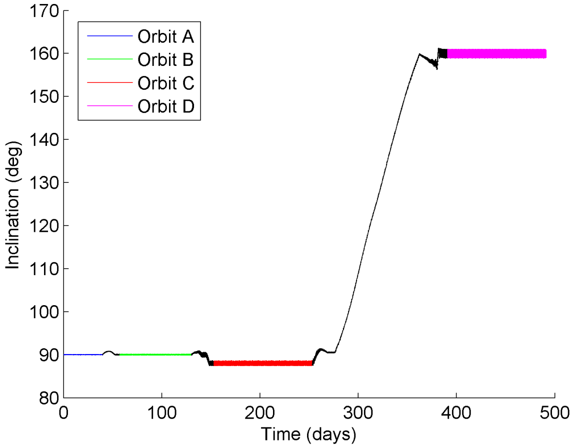


Figure 8: Time history of orbit inclination for proximity operations at Psyche.

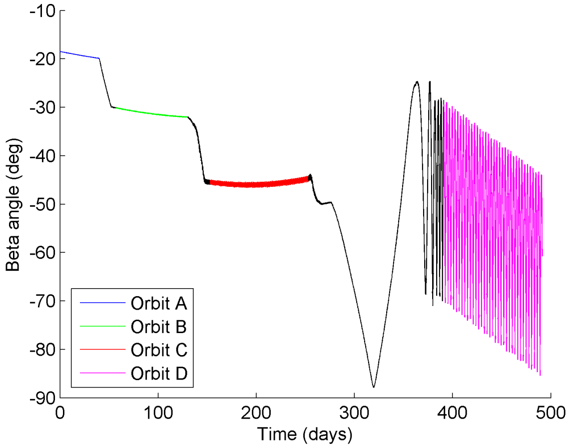


Figure 9: Time history of beta angle for proximity operations at Psyche.

IV. Spacecraft Description

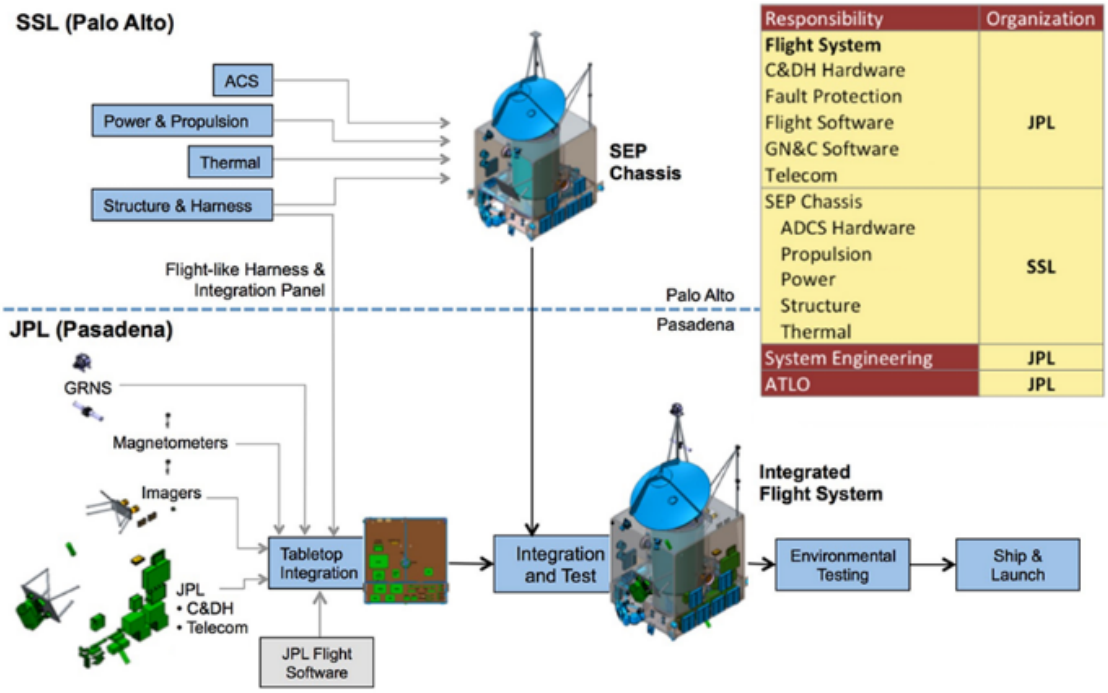
A. Spacecraft Overview

The only Discovery-class mission to utilize electric propulsion was Dawn, which was launched in 2007 and is currently under an extended mission at Ceres. Initially selected in 2001 as part of the 9th Discovery selection, Dawn utilized the NSTAR thruster, an electrostatic ion thruster that was previously utilized on the Deep Space 1 probe, launched in 1998. The use of the NSTAR thruster on Dawn provided a substantial savings in propellant mass and the ability to visit two asteroids, while also enabling a broader and more flexible launch period than more conventional methods utilizing chemical propulsion.[24]

In the years since the development of the NSTAR thruster, there have been considerable advances in the field of electric propulsion. Commercial satellite manufacturers have helped spur these advances, driven by the desire to maximize product value by lowering launch vehicle costs, maximizing on-orbit life, or a combination of both. Several satellite manufacturers offer integrated power and electric propulsion systems that have been qualified and flown on-orbit. These systems offer high reliability, strong flight heritage and a high production volume through their commercial product line, all traits that are strongly valued in a Discovery-class mission.

With these trends in mind, it was determined during the early conceptual design that the Psyche spacecraft design could benefit from a power and propulsion subsystem from a commercial satellite provider. For Psyche, ASU and JPL have partnered with Space Systems/Loral (SSL), a commercial satellite manufacturer with extensive experience in both electric propulsion and high power spacecraft. To date, SSL has flown 29 spacecraft with electric propulsion and over 20 spacecraft with solar array capabilities greater than 20 kW. The Psyche spacecraft design is based on the SSL 1300 platform, a venerable spacecraft bus with over 100 launches dating back to its first flight in 1989. The 1300 bus design has evolved substantially in the last three decades, particularly in the areas of power and propulsion.[25]

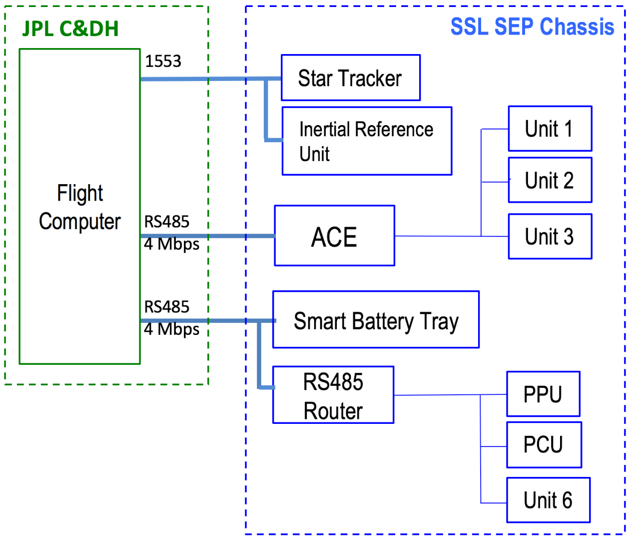
In a similar fashion, JPL has demonstrated experience both building and operating interplanetary spacecraft. Psyche would take advantage of this experience by utilizing JPL's deep-space heritage command and data handling (C&DH) hardware, telecommunications and Flight Software (FSW) for the spacecraft. JPL built the C&DH subsystem for the Curiosity Mars Rover and has successfully operated it in space and on the surface of Mars since 2011. A modified version of this C&DH system was flown on SMAP, which has operated in Earth orbit since 2015. The combination of JPL's deep-space heritage C&DH subsystem with SSL's EP, power, and structure subsystems leads to the spacecraft architecture in Figure 10. The resulting design reduces implementation risk by preserving the twin virtues of SSL's 10+ years of success flying commercial SEP: low cost-risk and flight proven mission reliability.



Responsibility	Organization
Flight System	JPL
C&DH Hardware	
Fault Protection	
Flight Software	
GN&C Software	
Telecom	
SEP Chassis	SSL
ADCS Hardware	
Propulsion	
Power	
Structure	
Thermal	
System Engineering	JPL
ATLO	JPL

Figure 10: The Psyche spacecraft reflects a partnership between JPL and SSL that builds on the strengths of each organization

JPL is responsible for overall systems engineering for the spacecraft. SSL produces a "SEP chassis" on their spacecraft production line in Palo Alto. It comprises the composite core structure, solar arrays, power subsystem, propulsion subsystem, ACS sensors and actuators, and thermal subsystem. Per standard SSL procedures, the SEP chassis would be acceptance tested at the command level before being shipped to JPL. JPL would produce the C&DH and telecom subsystems and all flight software including fault protection; integrating and testing these elements with the payload in a tabletop environment. JPL would re-integrate these elements and the payload onto the SEP chassis before system-level functional and environmental test and delivery for launch. JPL is responsible for final spacecraft assembly, test, and launch operations, and final assembly would occur at JPL's spacecraft assembly facility in Pasadena, CA.



Note: redundant units are not shown in this diagram

Figure 11: Psyche maintains clean, simple electrical interfaces between the SEP Chassis and JPL's C&DH system

Key to this architecture is a simple C&DH interface between the SEP chassis and JPL's C&DH system that minimizes complexity and maximizes the heritage of the electrical interfaces used across the spacecraft. The electrical interface between the JPL flight computer and the SEP chassis is straightforward, with two standard RS-485 lines and one 1553 digital communications bus crossing the interface to the SEP chassis. There are primary and redundant flight computers, and the SEP chassis incorporates primary and redundant ACEs and RS485 routers that relay commands and collect telemetry from units in the SEP chassis and return them to the flight computers. The ACE and router are firmware driven devices that contain no flight software. ACS sensors in the SEP chassis (the star tracker and inertial reference unit) return data directly to the flight computers via a standard 1553 data bus. All connections are redundant and cross-strapped to prevent faults on one side of the interface from causing loss of functionality on the other. This allows Psyche to tolerate to multiple faults that occur independently in JPL and SSL hardware without loss of functionality.

This C&DH architecture reduces the development risk associated with the SEP chassis in several ways. First, it ensures that all units on the SEP chassis utilize the same heritage electrical interfaces used on SSL's GEO spacecraft. Second, the limited number of electrical connections greatly simplifies design and testing of the interfaces between the SEP chassis and the JPL flight computer. Third, the digital interface allows SSL to fully verify the SEP chassis end-to-end, from the RS485 interface to the end sensor/actuator, before the chassis is delivered to JPL for integration. This allows full verification prior to delivery, cleanly separates test responsibilities between JPL and SSL, and supports a well-defined spacecraft assembly and test flow for the spacecraft.

The SSL 1300 bus can support propulsion subsystem configurations that utilize solely chemical or electric propulsion, as well as a hybrid configuration that utilizes both. Psyche would use electric propulsion for three-axis momentum control and cold gas xenon thrusters for safe mode control, and therefore require no chemical propulsion system. This allows the SEP chassis to accommodate Psyche's relatively large xenon propellant load within SSL's composite structure, which is qualified for a broad range of launch vehicles, including the Atlas V and Falcon 9. The majority of the power subsystem comes from SSL's product line, with minor modifications to efficiently accommodate the wide voltage variations from the solar array over the course of cruise phase. A more detailed discussion is provided below.

The thermal loads experienced from the avionics and payload in the Psyche spacecraft would be relatively modest, dominated by the bus units. A typical communications satellite of similar size would carry a multitude of high power/high thermal dissipation communications payload components, such as power amplifying Traveling Wave Tube Assemblies (TWTAs), radio frequency (RF) switching, signal processing electronics and waveguide runs. This payload equipment would amount to several hundred kilograms of mass, as well as kilowatts of power consumption and thermal dissipation. Psyche's thermal design also uses thermal louvers to keep the spacecraft from becoming too cold when far away from the Sun. Thermal louvers are passive mechanical shutters placed over thermal radiators that open to provide a clear view to space when warm and close to limit radiative cooling when cold. The Psyche louvers employ the same vendor that provided the louvers for the Juno spacecraft.

B. Propulsion Subsystem

Psyche would utilize SSL's SPT-140 Hall thruster system, which was flight qualified by SSL for its commercial spacecraft product line in 2015. The SPT-140 completed life qualification for Psyche to NASA standards in 2016 and is scheduled for first flight on an SSL spacecraft in 2017.[27] There are seven flights of the SPT-140 system currently planned before Psyche is launched in 2022.

During Step 1 development for Psyche, JPL performed an evaluation of the performance and operability of the SPT-140 thruster[26] outside of the standard 3.0 and 4.5 kW throttle points used in the commercial application.[27] This test, performed with a development model thruster (DM4), focused on measuring the performance and cathode operation at lower powers, which had not been investigated on a high-fidelity model thruster similar in design to the flight model thruster. The DM4 thruster operated stably at discharge powers as low as 225 W and throttled easily over the full range of powers. An important finding was that at powers below 1000 W the cathode-to-ground voltage became increasingly negative, and that this could be ameliorated by adding either additional cathode mass flow or cathode ignitor current. Performance data from this test were used in building the throttle curves used for mission design in the proposal.

Following this successful test, a series of additional risk-reduction tests were performed at JPL.[28] Although the SPT-140 thruster is capable of operating over a wide range of throttle levels, the xenon flow controller (XFC) that is paired with the commercial system does not have the dynamic range to support low power throttle levels. Therefore, a new flow controller approach is necessary for deeply-throttled missions like Psyche. SSL modified the flow control tray of the PPU-140 to drive a proportional-flow-control-valve-based XFC, and the PPU-XFC-thruster system successfully demonstrated startup, closed-loop throttling control from 800 to 4500 W, and shutdown of the DM4 thruster. A qualification model thruster (QM002) was also used for more extensive investigation of operation at low power, including a 27-hour test of thruster stability at 800 W and plasma plume diagnostics to obtain data necessary for life modeling. Throttled performance of the QM002 thruster was similar to the DM4. A summary of the Psyche-specific modifications to the commercial SPT-140 system is given in Table 4.

A final risk-reduction activity that was conducted was an extension of the SPT-140 life test.[27] After conclusion of the planned life test for commercial use, the QM001 thruster was successfully operated for 250 hours each at 900 W and 1000 W discharge power, then for an additional 470 hours at 4500 W discharge power. At the conclusion of the test QM001 had operated for 10,371 hours and processed 500.3 kg of xenon. The total SPT-140 life test, including this life test extension, demonstrated by test 150% of the planned throughput per engine for the Psyche mission.

Risk-reduction activities on the SPT-140 subsystem will continue through Psyche's development. For example, the performance of the SPT family of thrusters is known to be affected by vacuum facility background pressure, and these effects need to be characterized for Psyche.[28,29,30] A test of the QM002 thruster was recently conducted to measure performance at several powers spanning the planned usage profile, and these data will ultimately be used to estimate the performance of the thruster in the space pressure environment. Near-term flights of the system on commercial spacecraft will also provide information on in-space performance at the 3.0 and 4.5 kW power levels.

Together, these tests demonstrated that the SPT-140 provides the performance, lifetime, and throttle range necessary to meet the requirements of the Psyche mission concept. Further details on the development and qualification of the SPT 140 system and its adaptation for Psyche are included in Ref. 31.

Table 4: Summary of Psyche Specific Modifications to the SPT-140 System

	Requirement		Hardware Modification for Psyche	Notes
	SSL Commercial Satellite	Psyche		
Thruster Maximum Discharge Power	4500 W	4500 W	None	None
Thruster Minimum Discharge Power	3000 W	900 W	None	Demonstrated by test
PPU discharge power set points	4500 & 3000 W	Variable 900 W to 4500 W	None	Enabled by modular design
Xenon Flow Control Method	Thermothrottle flow controller (TXFC)	Proportional flow controller (PFCV) with variable set points	Change from thermothrottle to proportional flow control valves	Flight heritage PFCV replaces TXFC
Xenon Flow Control System	Provides two set points via thermothrottle	Provides continuous variable set points via proportional control	PPU flow control tray modified to control PFCV	Demonstrated by breadboard test
Life/Throughput	8000 hrs ~480 kg	500 kg	None	Life test extension performed successfully

C. Power Subsystem

For Discovery missions, it is critical that there be high heritage not just for the thruster, but also for the overall solar electric propulsion system.[4] A key difference between SEP systems flown in Earth orbit and those flown in deep space is the need to accommodate variable voltage from the solar arrays. SSL's GEO spacecraft use a shunt limited system to provide power from the array to the spacecraft bus, including the EP system, at a regulated voltage of ~100 V. Shunt limited systems work efficiently when the peak power operating voltage of the strings on the array is close to the target voltage for the bus. However, solar cell voltage depends strongly on cell temperature and is also a function of light intensity, and therefore varies with distance from the Sun. On Psyche, the peak-power voltage of the array would vary from 65 to 100 V. The Power Processing Unit (PPU) for the SPT-140 is qualified to receive power from a 100-V regulated bus and is therefore incompatible with this voltage range. Efficiently accommodating wide voltage variations from the solar array is a primary challenge for deep space solar power systems.

The solution to this incompatibility comes directly from SSL's GEO spacecraft. In eclipse, these spacecraft use a Power Control Unit (PCU) that incorporates discharge converters to boost voltage from batteries to create a regulated 100-V bus. Because the voltage range to be accommodated for Psyche (65 to 100 V) is enveloped by this GEO application (40 to 100 V), these discharge converters can be repurposed without modification to boost the array voltage on Psyche to create a 100-V regulated power bus regardless of distance from the Sun. This "boost-regulated" architecture is shown in Figure 3

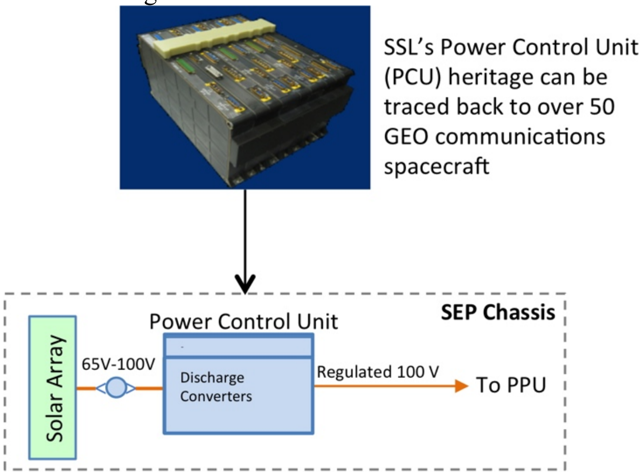

SSL's Power Control Unit (PCU) heritage can be traced back to over 50 GEO communications spacecraft

Figure 3: Discharge converters from SSL's GEO heritage power control unit boost solar array voltage and create 100 V regulated power for the PPU

The discharge converter is compatible with this application without changes. However, there was risk associated with this architecture because connecting the discharge converter to a solar array is a departure from the heritage GEO application. This risk was mitigated in Step 2 development by conducting two system level risk reduction tests using a modified engineering qualification model PCU, an engineering model PPU-140, and an SPT-140 simulator. In the first test, these units were connected to a solar array simulator at SSL. Simulated thruster firings demonstrated stable power system operation while firing a simulated SPT-140 thruster. In the second test, the units were connected to live solar arrays at JPL's Electric Propulsion laboratory. Again, simulated thruster firings demonstrated nominal and stable system operation. SSL has flown dozens of discharge converters in space, so the cost of this hardware is well understood, and the overall cost-risk associated with this architecture is low. This flight history, combined with risk reduction tests, provides solid system-level heritage for Psyche's SEP system.

A single lithium ion (Li-Ion) battery provides power during eclipses. Psyche's battery would be the SSL heritage battery used for GEO missions, which is a single string of Li-ion cells. Each cell incorporates a cell shorting device which is able to bypass a failed cell in the event of a cell failure. As mentioned above, the battery voltage is up-converted to a regulated 100V bus by a dedicated set of discharge converters, which is separate from those used to boost solar array voltage. To charge the battery during sunlight operations, a charge converter in the PCU would down-convert regulated 100V bus power to provide charge power. Charge control would be provided autonomously by the autonomous battery management software in the Psyche Compute Element (PCE).

SSL's heritage battery is mounted with a battery tray. The battery tray provides battery cell voltage telemetry, battery temperature monitoring and control, and battery cell balancing functions. Battery cell voltage telemetry is used by the autonomous battery management software to control battery charge levels. Thermal control software in the PCE would read battery temperatures and provide the battery tray commands to keep the battery at specific temperatures. The battery cell balancing function would bleed off excess battery cell current to keep all battery cells from diverging to maximize available battery power.

During sunlight operations, solar arrays would provide power to Psyche. Psyche would have two solar array wings and each wing would have five panels. Triple-Junction Solar Cells would be wired in series strings to provide 65 to 100 volts, depending on distance from Earth, and strings would be connected in parallel to provide solar array circuits. Each solar array circuit would be connected to a sequential shunt circuit in the PCU. These solar arrays can provide 20kW of power at Earth and 2.3kW of power at Psyche.

The key to this power system lies in optimizing the selection of the initial voltage such that existing off-the-shelf hardware from commercial geosynchronous applications designed to operate on 100V input power can be directly applied to mission trajectories of varying solar intensity; resulting in a SEP powertrain tuned to impose the lowest losses at the point at which the power available is at its minimum. An enabling feature of the power system design is the selection of a lower than 100V initial voltage for the solar array at the start of the mission, when the spacecraft is closest to the sun. By design, at the beginning of life, when solar fluence and array output power are highest, discharge converters boost the array output voltage to the regulated bus voltage of 100V. The resulting power conversion losses can be tolerated easily by the spacecraft, as many kilowatts of excess power are available at beginning of mission.

Over the course of the mission, as the spacecraft moves away from the sun, the optimal solar array peak power voltage rises as the arrays cool. The solar array is designed so that the array's peak power producing voltage, including solar array degradation and low intensity illumination affects, reaches the 100 V at end of mission. At this point, because the array voltage matches the bus voltage, the power conversion boost stage is no longer needed, and is replaced with a diode pass-through circuit from the solar array to the PPU. This eliminates boost stage conversion losses, thus conserving power when array power is at its minimum and all available power is required for PPU operation. Effectively, the boost converter efficiency increased from 97% to 99% as the spacecraft approaches Psyche, maximizing power available for science operations.

This patent pending SEP power train design trades higher losses when excess power is abundantly available, and highest efficiency when the available solar power is low, in return for flight proven hardware that is more economical than sophisticated dedicated deep space specific peak power tracking approaches that strive to minimize power train losses over the entire mission. This solution ensures that the power train losses are reduced to the lowest possible level at the minimum available power point which occurs at the furthest distance from the sun.

To provide power to science instruments and attitude control units, a low voltage bus is used to provide a regulated 31V bus. The SSL heritage low voltage bus uses multiple low voltage DC/DC converters which take the regulated 100V bus down to a regulated 31V bus. From the converters, a fusing network provides fused power to the Psyche science instruments and attitude control units such as reaction wheels, start trackers, and gyros.

D. All-Electric Attitude Control

The Psyche all-electric Attitude Determination and Control System (ADCS) would provide pointing of the spacecraft body during the planned mission phases including: cruise thrusting, cruise coast, science orbit and during science orbit transfers. ADCS hardware would be based closely on existing systems used on commercial satellites that are compatible with the spacecraft ADCS requirements. In addition to the SPT-140 thruster system described above, the spacecraft would include redundant Star Sensor Assemblies (SSA), Inertial Reference Units (IRU), Coarse Sun Sensors (CSS), and Reaction Wheel Assemblies (RWA), along with Solar Array Drive Assemblies (SADA), hall thruster gimbals (DSM) and a Xenon Cold Gas System (CGS).

The primary ADCS control mode would use the SSA and IRU data blended in a Kalman filter to determine attitude and four 100 Nms RWAs to provide 3-axis control. Unlike Dawn and DS1, which used 2-axis EP gimbals for direct attitude control during thrusting, but like SSL's communications satellites, the baseline Psyche ADCS design would maintain 3-axis RWA control while thrusting and use the EP gimbal to direct the thrust vector through the vehicle Center of Mass (CM) and to produce torques for momentum management. The ADCS provides functions for commanding the SADAs to maintain Sun pointing of the spacecraft's two 5-panel solar arrays.

To support mission EP thrusting, the baseline ADCS design would provide the capability to follow a ground-defined thrust vector profile. EP thrust vector pointing errors caused by external torques are minimized by following the profile with the inertial orientation of SPT-140 thruster directly rather than with a body fixed "expected thrust" vector, as on some earlier missions.

1. Momentum Management

Along with attitude determination and control, the ADCS is also responsible for unloading and managing angular momentum stored in the spacecraft RWAs. During both cruise and orbital operations, momentum from disturbance torques on the spacecraft would accumulate in the RWAs and would have to be periodically unloaded. The primary disturbance torques are solar radiation pressure, "swirl" torque produced by the EP thruster while thrusting and gravity gradient torques. At a typical cruise thrust level of 230 mN, the SPT-140 is predicted to produce about 0.25 mN-m of swirl torque. Gravity gradient torques become significant once the spacecraft reaches a low science orbit, especially at the Earth communications attitude. Simulations indicate this could be mitigated (at the cost of sub-optimal array pointing) by adopting an alternate Earth pointing attitude that points the HGA to Earth while keeping the long axis of the arrays near the orbit plane. Magnetic torques from the solar or asteroid magnetic fields are not expected to be significant disturbance torque contributors.

The proposed ADCS design provides a momentum controller function that allows 2-axis "continuous EP unloading" of RWA momentum when an EP thruster is operating. The momentum controller would monitor the level and trend of the stored RWA angular momentum and command small offsets between the SPT-140 thrust line and the spacecraft CM, slowly unloading momentum in the two "reachable" axes to a desired value. Since it directly measures the momentum trend, this approach also compensates for any change or uncertainty in the location of the spacecraft CM. The momentum controller can be configured to create larger (~0.4 m) thrust line offsets to perform a 2-axis "fast EP unload". The proposed Psyche EP gimbals provide sufficient range of motion to accomplish a "fast EP unload" in about 15 minutes.

Since an EP gimbal would be located on either side of the spacecraft with roughly mirror image geometry to the CM, combining a pair of 2-axis unloads using opposing thrusters would provide full 3-axis momentum control. Alternatively, a single EP thruster and gimbal could provide full 3-axis momentum control by using an unload-turn-unload approach, turning the spacecraft between two EP unloads.

During cruise coast where swirl torque is absent, momentum accumulation would be dominated by solar radiation pressure and the proposed RWAs have capacity to store many days of disturbance torque. RWA unloads would occur every few weeks coordinated with a downlink activity using the "fast unload" capability.

During cruise thrust arcs, EP thruster swirl torque will dominate the momentum accumulation. The ADCS momentum controller would use "continuous EP unloading" to limit disturbance torque accumulation in the two axes transverse to the thrust line while the accumulated thrust-line momentum (mostly swirl torque) would be periodically unloaded using the "fast EP unload" capability. When the thrust line momentum reaches a preset operational threshold, the EP thruster currently in use for mission thrusting would be shut down while an EP thruster mounted on the opposite side of the spacecraft would be selected and used to perform the "fast EP unload". The magnitude and direction of the ΔV imparted during EP unloads would be predicted in advance and accounted for in the mission thrust plan. Simulations suggest swirl torque unloads would be required about once per day during early cruise thrusting when the available power and swirl torque are largest.

V. Conclusion

(16) Psyche is a unique body in the solar system that is composed almost entirely of metal. *Psyche: Journey to a Metal World*, the latest mission selected by NASA for implementation as part of the Discovery Program*,* would explore for the first time what a metal world looks like, how was it created, and how its formation relates to the other planets in the solar system. As potentially the only exposed metal core in the solar system, Psyche may provide answers to fundamental questions on how the planets formed that cannot be answered in any other way except by visiting this unique world.

The planned Psyche mission is enabled by electric propulsion and would use SPT-140 Hall Thrusters to rendezvous and orbit (16) Psyche. The Psyche spacecraft requires no chemical propulsion and, once launched in 2022, would be the first mission to use Hall Thrusters beyond lunar orbit. This paper described the ongoing development of the Psyche mission concept and describes how Psyche uses commercially provided solar power and electric propulsion systems to address the unique challenges posed by this mission. It described the development of the mission's low-thrust trajectory and how the flexibility provided by electric propulsion has allowed the design to accommodate the changing requirements placed on the project during development of the mission concept. It also described how Psyche would use a unique spacecraft design that combines SSL's experience in high power electric propulsion systems with JPL's experience building highly autonomous spacecraft for deep-space. The architecture is built around a SEP chassis, derived from SSL's GEO product line, that is coupled with JPL's deep-space heritage C&DH and FSW to form the Psyche spacecraft bus. Finally, it discusses the all-electric attitude control strategy that allows Psyche to fly without the use of chemical propulsion. Together, these elements provide a robust baseline design architecture that maximizes heritage, leverages the strongest experience bases within the partner organizations, and minimizes risk across the design, thus providing a firm basis for future development of the planned Psyche mission.

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