Overview of the Spacecraft Design for the Psyche Mission Concept

William Hart[1], G. Mark Brown[2], Steven M. Collins[3], Maria De Soria-Santacruz Pich[4], Paul Fieseler[5], Dan Goebel[6], Danielle Marsh[7], David Y. Oh[8], Steve Snyder[9], Noah Warner[10] and Gregory Whiffen[11]
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109

Linda T. Elkins-Tanton[12], James F. Bell III[13]
Arizona State University
PO Box 871404
Tempe, AZ 85287

David J. Lawrence[14]
Applied Physics Laboratory
Johns Hopkins University
11100 Johns Hopkins Road
Laurel, Maryland 20723

Peter Lord[15], Zachary Pirkl[16]
Space Systems/Loral, LLC
3825 Fabian Avenue
Palo Alto, CA 94303

Abstract — **In January 2017, Psyche and a second mission concept were selected by NASA for flight as part of the 14th Discovery mission competition. Assigned for an initial launch date in 2023, the Psyche team was given direction shortly after selection to research the possibility for earlier opportunities. Ultimately, the team was able to identify a launch opportunity in 2022 with a reduced flight time to its destination. This was accomplished in large part to crosscutting trades centered on the electrical power subsystem. These trades were facilitated through the Psyche mission's planned use of Solar Electric Propulsion (SEP), which enables substantial flexibility with respect to trajectory design. In combination with low-thrust trajectory analysis tools, the team was able to robustly converge to solutions with a higher fidelity and accuracy of results. These trades also took advantage of the 1300 series product line produced by Space Systems Loral (SSL), which enabled power growth while maintaining strong system-level heritage through its modular design that has been utilized on a large number of geostationary (GEO) communications satellites.**

This paper presents an overview of the Psyche mission concept, and the unique architecture that enables the use of commercially developed electric propulsion and space power systems from Space Systems Loral to provide flexibility in mission design. This paper then discusses the trades that allowed the Psyche team to meet a 2022 launch date.

TABLE OF CONTENTS

978-1-5386-2014-4/18/$31.00 ©2018 IEEE
Predecisional information for planning and discussion only

1. INTRODUCTION

Started in 1992, NASA's Discovery program has demonstrated the science benefits that may be attained through cost-capped, competitively awarded exploration missions beyond Earth orbit. In over twenty years since the launch of the first mission, NEAR Pathfinder, there have been a compelling list of successes, such as Mars Pathfinder, Lunar Prospector, Genesis, Deep Impact, Stardust, Kepler, GRAIL and MESSENGER [1]. One of the more recent missions, Dawn, continues to demonstrate through operations at Vesta in 2012 and Ceres in 2016 the unique value that SEP (Solar Electric Propulsion) can provide to missions that are otherwise impractical or impossible to conduct within financial constraints using other methods of propulsion [2].

In January 2017, the proposed mission *Psyche: Journey to a Metal World*, led by Principal Investigator (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 concept 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 every flown on a single NASA spacecraft.

There have been a number of developments since the selection of the Psyche mission concept, including the development of a new trajectory to support an earlier 2022 launch opportunity. This paper describes the Psyche mission concept, including the scientific objectives, mission architecture, highlighting the ongoing development that has taken place since its selection for implementation. Section 2 provides an overview of the Discovery program, and the selection process. Section 3 outlines the science and objectives of the Psyche mission and Section 4 describes the payload instruments. Section 5 outlines the mission design for cruise and proximity operations, while Section 6 describes mission implementation, overall spacecraft architecture, the subsystems and their interfaces.

2. BACKGROUND

In November 2014, NASA initiated a two-step competition to award the next Discovery mission with the release of the Discovery 2014 Announcement of Opportunity (AO). Twenty-seven mission proposals were submitted into Step 1, and in September 2015, NASA announced the down-selection to five proposals for Step 2 and awarded each team $3M to initiate "Phase A" and conduct concept development studies. It was announced that there was the potential for multiple programs to be chosen for Phase A implementation for the first time since the 2000 Discovery solicitation that resulted in the selection of the Dawn and Kepler missions [3].

The selection of missions for Discovery is a multi-step competitive process governed by an AO that lists evaluation criteria for each selection round. In 2014 (the current round), the selection criteria for Step 1 were defined as a) the scientific merit of the proposed investigation, b) the scientific implementation merit and feasibility of the proposed investigation, and c) the Technical, Management, and Cost (TMC) feasibility of the proposed approach for mission implementation, including cost risk.

The weighting used for selection criteria in Step 1 was: 40% for scientific merit, 30% for scientific implementation merit and feasibility, and 30% for TMC feasibility. In Step 1, the Psyche mission concept was judged to have compelling science, low risk in TMC, and was rated Category I overall. The weighting of the selection criteria changed in Step 2 to become less science-centric and more implementation/risk management-centric. The challenge for Step 2 was to find all sources of potential cost growth and technical uncertainty (i.e., risks) and effectively mitigate them to produce a simple, low-risk, highly implementable mission concept. The maximum allowable mission cost is strictly capped. For Discovery 2014, the cap is nominally $450M for project phases A-D, subject to adjustments, and each proposal is required to maintain a minimum of 25% cost reserve at each Key Decision Point in the project life cycle.

While SEP may enable a scientific investigation, it is only a weak factor in the evaluation of science merit, and therefore plays a supporting role to the science in the Step 1 evaluation. However, SEP is a strong factor in the evaluation of TMC risk and therefore plays a primary role in the Step 2 evaluation. The need for low risk, combined with the expectation that one should use mature technology, leads mission architects to seek solid SEP *system level* heritage and high Technology Readiness Level (TRL) when selecting SEP systems for the Discovery AO [4].

3. SCIENCE AND OBJECTIVES

This mission would explore the large asteroid (16) Psyche* (~279 x 232 x 189 km) that orbits the Sun at ~3 AU, in the outer asteroid belt [5]. Though Psyche has never been imaged in visible light as more than a white point, or two or three pixels in the Hubble space telescope, Psyche is known to be made almost entirely of Fe-Ni metal, rather than the silicate rock and ice that composes almost all other small worlds.

Several density estimates of Psyche have been made, including 4,500 ± 1400 kg m^{-3} [5], 6,980 ± 580 kg m^{-3} [6], 6,490 ± 2,940 kg m^{-3} [7] [8], and 7,600 ± 3,000 kg m^{-3} [9]. These high-density estimates contrast strongly with the estimates for silicate rock asteroids: 1,380 kg m^{-3} for C-type and 2,710 kg m^{-3} for S-type asteroids, roughly one-third to one-half their parent-rock density of around 3,300 kg m^{-3} [10]. Most asteroids, therefore, appear to be fractured or have otherwise high porosity, and so their bulk density is lower than their pure material density.

Psyche's reflection spectra is relatively flat and featureless, consistent with a metal body with about 10% silicate rock on its surface [11]. Finally, metal composition is further indicated by a radar albedo of 0.42 [12] and a high thermal inertia of ~120 J m^{-2} $S^{-0.5}$ K^{-1} [13], where in comparison the silicate asteroids Ceres, Pallas, Vesta, Lutetia all have thermal inertia from 5 to 30 J m^{-2} $S^{-0.5}$ K^{-1}.

The leading hypothesis for Psyche's formation is that it is the metal core of a small planet that, rather than being incorporated through accretionary impacts into the growing planets early in the solar system, had its rocky exterior stripped away by destructive "hit and run" impacts. Multiple model runs of solar system formation indicate that between four and eight hit-and-run impacts are needed to strip the silicate rock from the metal core of a planetesimal [14]. Thus, modeled solar systems sometimes contain a Psyche-like metal body when complete, and occasionally two Psyches, and often none. Psyche is an unlikely body, and therefore compelling for exploration.

The Psyche investigation has three broad goals: (1) Understand a previously unexplored building block of planet formation: iron cores; (2) Look inside the terrestrial planets, including Earth, by directly examining the interior of a differentiated body, which otherwise could not be seen; and (3) Explore a new type of world. For the first time, examine a world made not of rock or ice, but of metal. Humankind has never visited a metal world: all previous space missions have visited rocky, icy, or gas-covered worlds.

* The International Astronomical Union (IAU) designation is (16) Psyche. For clarity, we will use Psyche throughout this paper.

The Psyche mission proposed science objectives are:

A. Determine whether Psyche is a core, or if it is unmelted material.
B. Determine the relative ages of regions of Psyche's surface.
C. Determine whether small metal bodies incorporate the same light elements as are expected in the Earth's high-pressure core.
D. Determine whether Psyche was formed under conditions more oxidizing or more reducing than Earth's core.
E. Characterize Psyche's topography.

By combining data from all instruments to answer each science objective, the conclusions are significantly strengthened. Psyche's mission objectives are met with significant margin by a payload of three high-heritage instruments and radio science:

Dual fluxgate magnetometers characterize Psyche's magnetic field while mounted in a gradiometer configuration on a fixed two-meter boom. The measurement of a magnetic field around Psyche would immediately confirm its identity as the core of a planetesimal; there is no other way the metal object could become strongly and coherently magnetized.

Redundant multispectral imagers (with Mars Science Laboratory Mastcam heritage) with clear and seven color filters provide foundational information about surface geology and composition as well as navigation. Stereo imaging using off-nadir pointing would be used to develop topographic maps.

A gamma-ray and two neutron spectrometers (with MESSENGER heritage) determine elemental composition, including the concentrations of iron, nickel, silicon, potassium, sulfur, and aluminum.

Radio science would map Psyche's gravity field using the X-band telecomm system and the spacecraft's response to Psyche's mass.

Determining whether or not Psyche is a core is the first objective of the proposed mission and may involve measurements from all the instruments. If Psyche was a core, it may well have produced a magnetic field [15] and such a field might have been recorded in its outermost, freezing layers, if it froze from the outside in. There is no other convincing way for Psyche to have a significant magnetic field recorded in its lid. Therefore, if the mission measures a magnetic field, Psyche is confirmed to be a core.

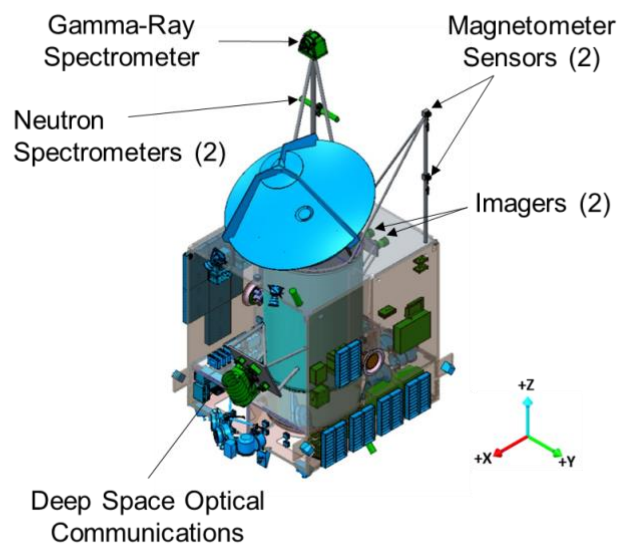

Figure 1. Psyche baseline payload instrument accommodation

Freezing from the outside inward is predicted with theory, and might also lead to the volcanic expulsion of immiscible sulfur-rich liquids onto Psyche's surface as freezing proceeds. The contraction of the liquid metal as it freezes might also produce contraction scarps in the frozen lid. Nickel content of the metal phase would be expected between 4 and 12 wt%, judging from iron meteorites. Thus chemical and physical models predict a suite of observables if Psyche is a core.

If, however, Psyche is not a core, it may be instead highly reduced, primordial metal-rich materials that accreted, but never melted. There are no samples of such material in the meteorite collection, though formation of bodies like this have been hypothesized [16]. This mission therefore has the exciting task of discriminating between two unlikely hypotheses for Psyche's formation; all outcomes would be highly significant scientifically.

4. PROPOSED PAYLOAD INSTRUMENTS

The Psyche Payload is planned to include three science investigations and a proposed NASA technology demonstration, accommodated as per Figure 1. The science investigations include a pair of Psyche Multispectral Imagers (PMI), a set of two Magnetometers, and the Gamma-Ray and Neutron Spectrometer (GRNS). These science investigations would provide data to help answer the primary scientific question, is Psyche a planetary core? The PMI has the additional role of providing images for optical navigation at Psyche. The NASA technology demonstration hosted by the Psyche mission is the proposed Deep Space Optical Communications (DSOC) payload, that would demonstrate a new telecommunications technology for high-rate data return from future NASA deep space missions.

A. Multispectral Imager

The Psyche Multispectral Imager (PMI), shown in Figure 2, consists of a pair of redundant medium-angle cameras that are mounted adjacent to each other on the spacecraft's –X panel and oriented to have a nadir-pointed field of view during nominal orbital operations around Psyche. Each camera consists of a camera head [charge coupled device (CCD) focal plane array and electronics], a 9-position filter wheel, a 148 mm focal length *f*/1.8 Maksutov (all spherical, fused silica elements), and a separate Digital Electronics Assembly (DEA) mounted separately inside the spacecraft.

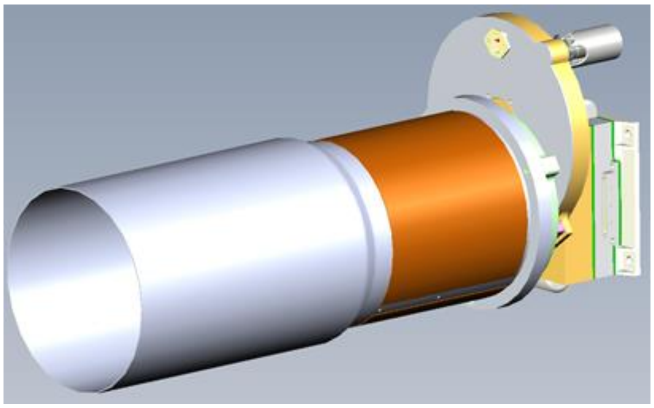

Figure 2. Illustration of the Psyche Multispectral Imager

PMI has high overall heritage. The camera heads, including the Kodak (now ON Semi) KAI-2020 CCD and associated electronics, as well as the DEA electronics, are build-to-print reflights of the camera heads and DEAs on the NASA Mars Science Laboratory Mastcam [17] and Mars 2020 Mastcam-Z [18] imaging investigations. The filter wheel is a ≈1.5x scaled-up version of the filter wheels from those same heritage camera systems, but with filter characteristics optimized for Psyche science goals, shown in Table 1. The telescope is a modified (longer focal length, faster *f*/#) version of the telescope flown on the NASA Mars Climate Orbiter Mars Color Imager (MARCI) investigation [19].

PMI images directly address all five of the Psyche mission's science objectives by:

A. Assessing the metal-to-silicate fraction using near-IR multispectral data;
B. Mapping statistically-significant numbers of impact craters to enable relative age datin of surface regions;
C. Searching for and characterizing the presence of key diagnostic sulfide minerals (like oldhamite) that could provide information on the oxidation conditions of Psyche's formation.
D. Characterizing the geology of a metallic world for the first time using panchromatic and color imaging, and
E. Characterizing the asteroid's topography through stereo imaging to search for additional diagnostic indicators of its formation and/or evolution.

The cameras also serve as the mission's primary Optical Navigation (OpNav) sensors, providing images of stars and Psyche on approach for Navigation team assessment. Two identical cameras would be flown for redundancy, not necessarily for simultaneous operations.

B. Gamma-Ray and Neutron Spectrometer

The Psyche Gamma-Ray and Neutron Spectrometer consists of gamma-ray and neutron sensors that provide global, and in some instances, spatially-resolved measurements of Fe, Ni, Si, K, S, Al, Ca, Th, and U concentrations on Psyche. Measurements of H and C are also possible, depending on their total concentrations. The GRNS sensors measure gamma rays and neutrons created when energetic galactic cosmic ray (GCR) protons impact the asteroid's surface. Gamma-ray and neutron spectroscopy has become a standard technique for measuring planetary surface compositions, having successfully made composition measurements of the Moon, Mars, Mercury, and the asteroids Eros, Vesta, and now Ceres [20] [21] [22] [23] [24] [25] [26].

The GRNS has two subsystems - a MESSENGER-heritage Gamma-Ray Spectrometer (GRS) and a Lunar Prospector heritage Neutron Spectrometer (NS), shown in Figure 3.

Table 1. Preliminary PMI Filter Characteristics

Filter	Wavelength (nm)	FWHM (nm)	Worst SNR	Exp. (msec)	Sum	Filter Objective
1	540	280	146	2.4	1x1	Unfiltered CCD QE for OpNav, topography and geologic characterization
2	437	50	146	17.7	1x1	Oldhamite detection and blue component of true color
3	495	25	147	19.3	1x1	Search for evidence of oldhamite
4	550	25	147	20.8	1x1	Oldhamite detection and green component of true color
5	700	50	146	23.9	1x1	Typical peak reflectance continuum and red component of true color
6	750	25	101	42.0	1x1	Search for evidence of low Ca pyroxene
7	948	50	103	42.0	2x2	Search for evidence of higher Ca pyroxene and characterize weak Psyche Earth-based spectral feature
8	1041	90	100	77.0	3x3	Search for evidence of olivine
9	-	-	-	-	-	Opaque "Sun safe" blocker

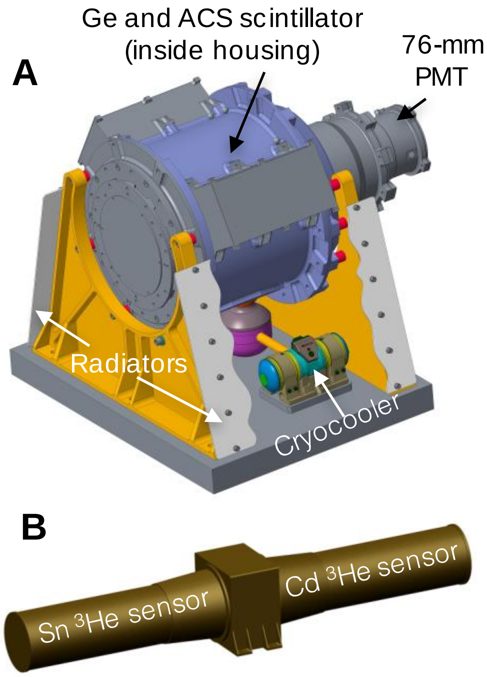

Figure 3. Illustration of the Psyche GRS (A) and NS (B).

The GRS consists of a high-purity germanium (HPGe) sensor surrounded by a borated plastic anti-coincidence shield (ACS). The HPGe sensor provides measurements of gamma-ray emissions from Psyche with excellent energy resolution (4.0 keV @ 1332 keV). The GRS is cooled using a long-life pulse-tube cryocooler designed and built by Lockheed Martin [27]. The ACS characterizes GRS-incident charged particles, primarily galactic cosmic ray (GCR) protons, for the purpose of removing GCR-induced backgrounds in the gamma-ray spectra via a veto rejection. At 1.3 body-radius orbital altitude, the ACS veto reduces the background continuum of the gamma-ray measurements by a factor of ~6 at 7 MeV and ~2.5 @ 3 MeV [28]. The ACS is also a sensitive neutron detector and provides a measure of both low-energy and fast neutrons. The NS uses two ^{3}He sensors, one covered in Sn and one in Cd, to provide unambiguous measurements of thermal and epithermal neutrons [29]. These sensors exhibit high sensitivity, are extremely rugged, and radiation tolerant, and have extensive spaceflight heritage. Both GRNS sensors are mounted on a two-meter boom to distance them from the gamma-ray and neutron background created by energetic particles interacting with the spacecraft and to provide an unobstructed field of view of Psyche. Because the GRS is more sensitive to spacecraft background, it is mounted at the end of the two-meter boom farthest away from spacecraft materials, and the NS is mounted halfway out on the boom.

Two Data Processing Units (DPUs) operate the instrument, and process and pass the GRNS data on to the spacecraft. The GRS and NS have separate DPUs, each of which would be mounted on the spacecraft deck. The DPUs are an updated version of the units used on MESSENGER with direct heritage to the boards used on the Van Allen Probes RBSPICE instrument [30]. Both DPUs contain board "slices" that are functionally identical to MESSENGER: a processor board, a low-voltage power board, and a high-voltage power board. The GRS DPU contains an additional controller board to operate the cryocooler.

While the GRNS contains many high-heritage components, there are some targeted risk-reduction activities currently in progress. A primary risk-reduction activity is carrying out early system-level environmental testing of the sensor and cryocooler to ensure the successful flight operation of this never-flown cooler. Second, while not a specific Psyche mission activity, we are conducting a parallel study to improve radiation damage mitigation procedures that were used for the MESSENGER GRS [31]. For this study, which is funded by the NASA Maturation of Instruments for Solar System Exploration Program [32] [33], we will irradiate three flight-like Ge sensors with 1 GeV protons at Brookhaven National Laboratory to simulate the effect of GCRs in space. We will then test mitigation procedures (e.g., high-temperature annealing) that will more effectively reverse the radiation damage caused by high-energy protons. The data obtained in this study will be used to implement flight-operation procedures for reversing the effects of radiation damage that are expected to accumulate during the cruise portion of the Psyche mission.

C. Magnetometer

The Psyche Magnetometer is composed of two identical high-sensitivity magnetic field sensors of the fluxgate type, located at the middle and outer end of a single two-meter fixed composite boom as notionally represented in Figure 1. This gradiometer configuration enables the rejection of meter-scale stray fields from the Spacecraft. Each sensor consists of two cores, three sense windings (one per axis), and three feedback windings. Each of the two identical electronics units (one per sensor) has its own chassis, and they are located inside the Spacecraft bus. The cores are driven by the FPGA through a drive circuit. An analog circuit conditions signals from the sense windings and feeds these to the FPGA to be digitized. The 2nd harmonic is then demodulated, which represents the ambient field and it is fed back to drive the feedback windings in the sensor to a near zero field. The FPGA also formats and transmits data to the redundant interfaces with the Spacecraft avionics.

The Magnetometer's role is to determine if Psyche is a core of a differentiated body by sensing an ambient field intensity in the Spacecraft environment of 1 nT to 10,000 nT in three axes. The anticipated sensor accuracy is 0.2 nT in 3-axes, and the data are digitized to provide ±0.1 pT and ±10 pT resolution in two selectable ranges of ±1,000 and ±100,000 nT, respectively. These ranges were chosen to optimize sensitivity while recording the full range of expected Psyche fields. The sensitivity of the sensor is limited by the system noise of 0.01 nT/√Hz at 1 Hz, and the instrument collects data with a sampling rate of 12 Hz during all science orbits. In addition to the gradiometry measurement technique, several other measures are in place to minimize the noise contamination from Spacecraft stray fields. These measures are implemented through a Magnetics Control Program. The cryocooler on the GRS boom is also a source of magnetic noise and it is the closest to the Magnetometer sensors (about 2 meters away). The magnetic field from this cryocooler was measured earlier in the project as part of a risk reduction activity and it was found to be insignificant at the Magnetometer sensor locations.

The Magnetometer has heritage from the Magnetospheric Multiscale Mission (MMS), ST5, and Polar, and the instrument has evolved from dozens of flight programs dating back to the Apollo era. Except for minor modifications applicable to Psyche (such as different dynamic ranges), the instrument is essentially the same as the units on MMS (currently operating) [34] and the units that have been delivered and successfully installed on InSight. In contrast to heritage sensors, however, the Psyche Magnetometer sensors may need a heater to survive and operate at the low temperatures encountered at Psyche. The design of a magnetically clean heater that can be mounted by the Magnetometer sensors has been identified the main risk to the instrument, and early design and test efforts are currently in place to mitigate it.

D. Deep Space Optical Communications Technology Demonstration

The Deep Space Optical Communications (DSOC) Project at the Jet Propulsion Laboratory (JPL) plans to perform a technology demonstration of optical communication between Earth based ground stations and the Psyche spacecraft from deep space at distances relevant to NASA's goals for solar system exploration. The optical communication link would be demonstrated during the Cruise Phase of the Psyche mission over Earth-probe distances ranging from 0.1 to over 2 astronomical units (AU). The DSOC concept is designed to support downlink data rates from as low as 0.2 Mbit/s to over 200 Mbit/s, and uplink data rates of approximately 1.6 kbit/s. The downlink rate is greatest at the start of the mission at close Earth-probe distances and scales with distance. DSOC would attempt to demonstrate the link over a variety of Earth-probe distances, for at least one year from launch.

The portion of the DSOC system that would be hosted as a Payload on the Psyche spacecraft is referred to as the deep space Flight Laser Transceiver (FLT) and is shown in Figure 4. There are several key elements of the FLT. First, a set of electronics for command and telemetry. Second, a Laser Transmitter Assembly (LTA) that emits a 4W average power at 1550nm. Third, a 22cm diameter Optical Transceiver Assembly (OTA) that acts as the primary DSOC telescope for sending and receiving signals. Fourth, a Photon Counting Camera (PCC) for receiving a weak (~100 femtowatts) 1064nm laser uplink signal. Finally, a set of active struts to mechanically isolate and perform fine pointing of the telescope, referred to as the Isolation and Pointing Assembly (IPA). All of these key assemblies have been built and tested in a laboratory setting.

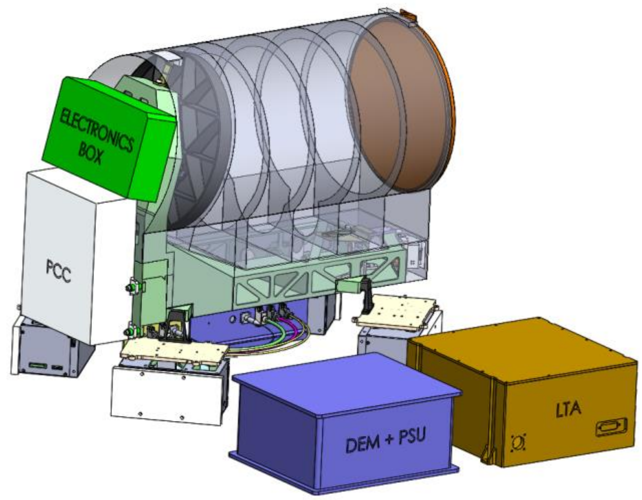

Figure 4. Illustration of the DSOC Flight Laser Transceiver (FLT) hardware

The DSOC FLT is co-boresighted on the Psyche spacecraft with the High Gain Antenna (HGA) for the spacecraft's primary X-band telecommunication system. This allows the spacecraft to use the two communication systems simultaneously, maximizing the efficiency of mission time spent when not thrusting. It also allows for real-time telemetry during attempted optical link demonstrations. Although the Psyche mission's primary communications link utilizes the X-band Small Deep Space Transponder (SDST), the DSOC is designed to be capable of supporting spacecraft uplink and downlink functions.

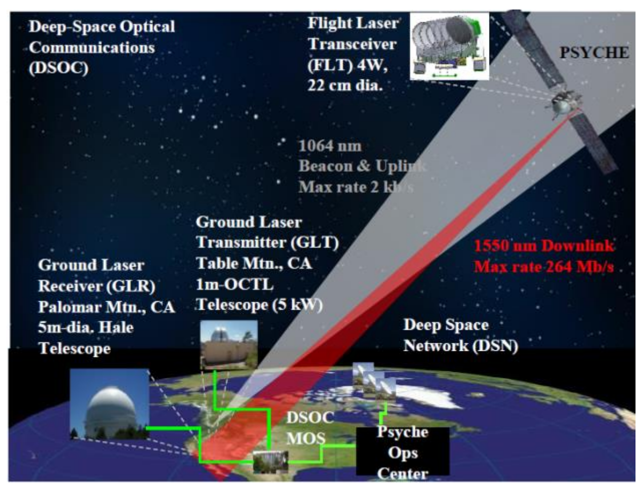

Figure 5. DSOC Flight and Ground Operations Concept

In order to perform optical links, two ground stations on Earth would be utilized (Figure 5). The Ground Laser Receiver (GLR) at Palomar Mountain would outfit the Hale Telescope with a photon counting receiver to detect the downlink from the spacecraft. The Grand Laser Transmitter (GLT) at the Table Mountain facility performs two functions. First, the GLT emits a 1064nm laser tracking beacon for the FLT to use as a pointing reference. Second, this same 1064nm laser is used for low-rate uplink to the spacecraft (~1.6 kbit/s). The FLT must track the beacon and then utilize the spacecraft's onboard ephemeris to point slightly ahead of the GLR in order to account for one-way light time as it emits the spacecraft downlink signal. Link demonstrations are approximately two hours in length each, and planned to be performed at a cadence of two to four times per month during the first year of the Psyche mission.

The DSOC team is currently preparing for Systems Requirement and Mission Definition Review, with a Preliminary Design Review planned for late 2018. The DSOC testbed is actively integrating prototype hardware to demonstrate beacon signal tracking, pointing algorithms and end-to-end information transfer.

5. MISSION CONCEPT DESIGN

A. Cruise Trajectory

The objective of the Psyche mission design effort is to deliver an adequate mass spacecraft (including margins) to asteroid Psyche in as short a flight time as possible. Constraints include a specified maximum allowed launch vehicle performance capability corresponding to an Atlas V 411 launched from Cape Canaveral, Florida. The actual launch vehicle to be used may be different. The proposal guidelines allowed for a higher performance category at additional cost. Launch was originally constrained to occur during the 2021 calendar year, ideally later in the year than earlier to facilitate the spacecraft construction schedule. A backup launch was sought in 2023 to allow for a major schedule slip or a secondary selection by NASA. Ultimately, NASA selected Psyche for its backup 2023 launch date.

All trajectory design for the Step 2 proposal and post-selection trajectory design work was completed with Mystic [35]. Mystic (not an acronym) uses a second order optimal control algorithm called Static-Dynamic Optimal Control (SDC) [36] based on Bellman's principal of optimality. SDC achieves both the necessary and sufficient conditions of optimality. Mystic is a high fidelity tool that has been used for all mission design and maneuver design work for the Dawn Discovery mission to Vesta and Ceres. Mystic has assisted other flight projects including the Cassini and Artemis missions.

A detailed analysis of all feasible trajectories in all of the years 2021 through 2024 was completed. The trajectory proposed for Step 1 of the Discovery mission selection process was not desirable for Step 2. It launched in late summer/fall of 2020 (too soon for the delayed Step 2 schedule margin) and required 5.3 years of flight time to reach Psyche capture in January of 2026. The trajectory used a single Mars gravity assist in May of 2023, delivering 1790 kg total spacecraft mass (including remaining propellant) to Psyche capture. Propellant for the interplanetary cruise was limited to 935 kg of xenon (deterministic) during Step 1.

In Step 2, the ideal propellant target was reduced to 915 kg for various reasons. A further trajectory limiting desire 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 science objectives.

Other constraints placed on the trajectory search included a maximum cruise duty cycle of 90%, a Psyche approach duty cycle of 50% (final 100 days before the first science orbit injection), post launch forced coast of at least 90 days for spacecraft check out, pre-Mars and pre-Earth flyby forced coast of at least 60 days, and post Earth and Mars flyby forced coasting of at least 15 days. For both the 2021 and 2023 opportunities, the solar array was constrained to four panels on each wing and assumed end of life LILT performance at all times. The spacecraft bus power draw (not available for thrusting) was assumed to be 780 watts.

The 2021 launch opportunity was discovered by Mystic. It

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

	2021 Opportunity E-E-M-P	2020 Opportunity E-M-P
Launch Period	August 1 – 20, 2021	November 21 – December 10, 2020
Launch C3	14.8 km^2/s^2	16.8 km^2/s^2
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	14,282 – 25,074 km, August 3, 2022	Not Applicable
Mars Gravity Assist	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 [End of Life (EOL), 1 AU]	15,979 Watts (four panels)	15,780 Watts (four panels)

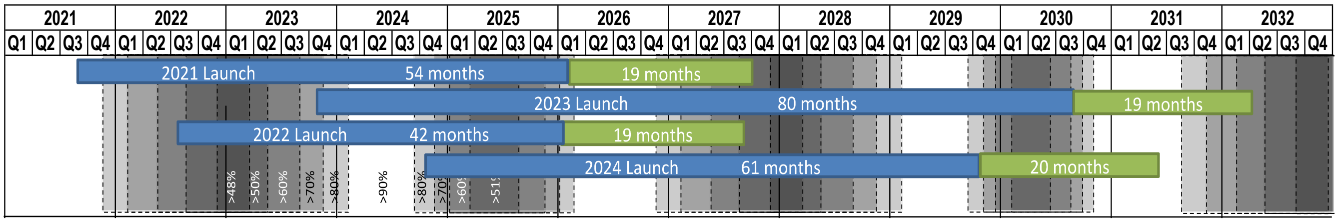

Figure 6. Percent of Psyche illuminated as a function of date. Ideal arrival dates are near the beginning of each white area. The bottom two trajectory timelines now represent the baseline and backup missions.

was found that a Mars flyby (or multiple Mars flybys) either did not provide adequate mass performance or resulted in long flight times. The flybys of both Earth and Mars are constrained to a minimum altitude of 500 km. Table 2 provides the characteristics of the proposed 2021 mission and the originally proposed 2020 mission for comparison.

The 2021 opportunity is superior in all regards compared to the initially proposed 2020 opportunity except for the new thermal requirements necessary to operate at 0.89 AU. Both opportunities arrive at essentially the same time during optimal lighting conditions. The shorter flight time in 2021 reduces cost and risk. A similar Earth-Earth-Mars-Psyche trajectory exists in 2023 to serve as a backup. The backup opportunity has similar characteristics in all regards to the 2021 opportunity except it cannot arrive at the start of optimal lighting conditions.

NASA selected Psyche to launch during our proposed backup in 2023. After selection, the new project was directed to investigate launches up to one year earlier (second half of 2022 being the most desirable). A higher performance launch vehicle was permitted. The project also decided to allow the possibility of using a five-panel (per wing) solar array in place of the proposed four-panel array. It was found that the increased power would make a very short flight time Earth – Mars – Psyche trajectory possible in 2022. The possibility of a higher performing launch vehicle provided less benefit. The 2022 opportunity is similar to the 2021 trajectory without the Earth Gravity assist. This trajectory fails to deliver adequate mass to Psyche with a four panel solar array, so was eliminated for consideration in the Step 2 proposal. The 2022 opportunity has the added advantage that it does not need to travel to heliocentric distance 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 3 provides the characteristics of the proposed 2022 mission and the 2024 backup mission.

NASA directed the project to adopt the 2022 launch as our primary launch period. This trajectory is significantly superior to both the 2021 and 2023 opportunities. The launch declination is relatively benign (the 2021 and 2023 opportunities launch -28.5 degrees south), the flight time is much shorter, and no excursion below 1 Astronomical Unit (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 6 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 7 illustrates the trajectory at the open of the new 2022 primary launch period mission. Thrust acceleration is indicated by the green arcs.

Figure 8 illustrates the trajectory performance over the 2022 primary launch opportunity. A twenty-day launch period would accommodate at least 1965 kg delivered to Psyche capture. Less than 915 kg of xenon propellant would be required to reach capture during the first half of the launch opportunity.

Table 3. Characteristics of 2022 and 2024 (Phase B) Launch Opportunities

	2022 Opportunity E-M-P	**2024 Opportunity E-M-P**
Launch Period (approximate)	August 1 – 20, 2022	September 18 – 27, 2024
Launch C3	14.5 km^2/s^2	13.6 km^2/s^2
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
Mars Gravity Assist	500 km, May 24, 2023	500 to 973 km
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)	19,970 Watts (five panels)	19,970 Watts (five panels)

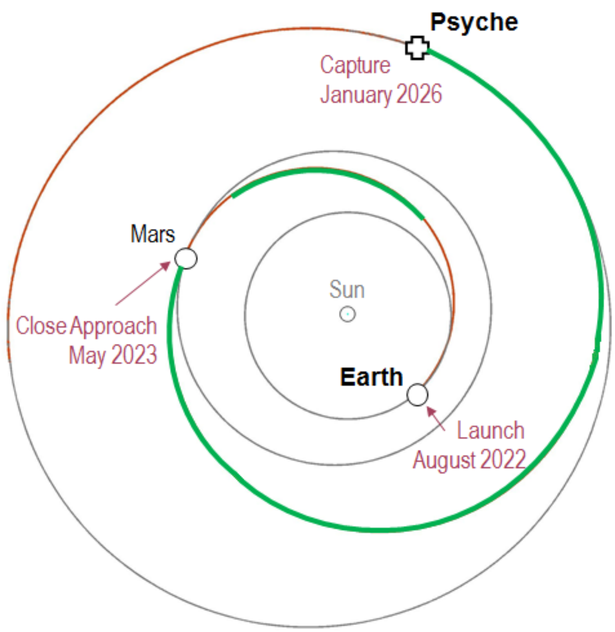

Figure 7. An example of a 2022 primary launch period (open) trajectory.

B. Proximity Operations

As Psyche is a previously unvisited body, it is not possible to sufficiently characterize the shape and gravity field of the body until after arrival. Therefore, operations planning of the science orbits needs to be robust to the uncertainties such as shape, density variations, pole orientation and rotation rate that currently exist.

Therefore, the orbit design consists of a series of progressively lower circular orbits; a recursive technique successfully demonstrated by Dawn [37] [38] [39]. 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. The notional campaign, shown in Figure 9 consists of four orbits over a total science operations period of 21 months.

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 for transfer. Orbit D, also stable, is inclined, retrograde, and at less than one body-radius altitude to produce satisfying GRNS measurements.

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

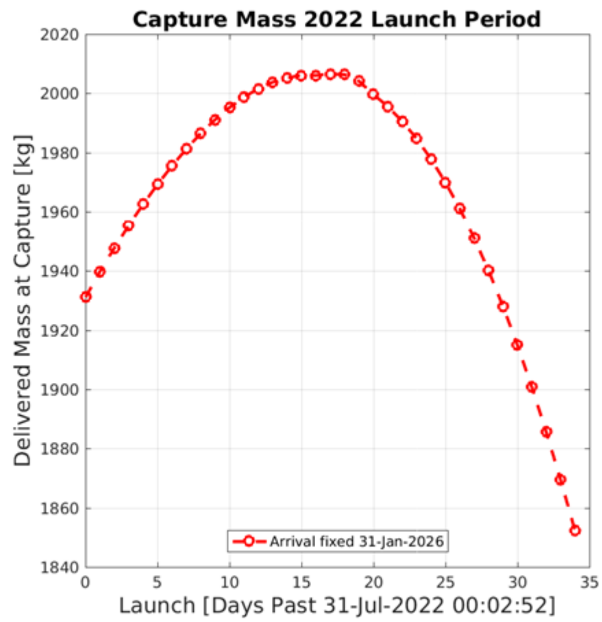

Figure 8. The mass performance of the proposed 2022 primary launch period

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.

More time is spent in Orbit C than required for science to avoid excessive eclipse durations in Orbit D. 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. 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.

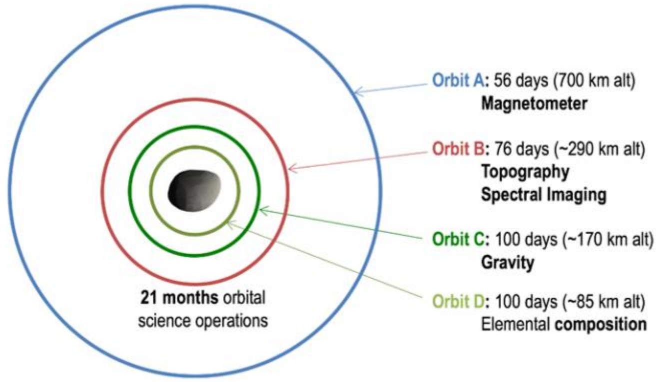

Figure 9. The planned Psyche Science Phase consists of four orbits at decreasing orbital altitudes

6. Mission Concept Implementation

A. Spacecraft Overview

The Psyche spacecraft is designed to host the three science instruments, transport them to Psyche, and then provide appropriate observing conditions and data management support during a 21-month science campaign at the asteroid. The spacecraft also accommodates the flight terminal of the proposed Deep Space Optical Communications (DSOC) technology demonstration, operating DSOC at various distances from Earth during the cruise to Psyche. In order to accomplish all of this within a Discovery-class budget, the Psyche project utilizes a Solar Electric Propulsion (SEP) Chassis from SSL, a high volume manufacturer of commercial spacecraft. SSL's product line includes the 1300 satellite bus, a family of long-life, high-power geosynchronous communications satellites. Psyche's SEP Chassis benefits from the extensive heritage and high volume efficiencies of SSL's current product line, reducing implementation risk and leveraging SSL's 10+ years of successfully flying Solar Electric Propulsion systems.

SSL's 1300 satellite series provides power and propulsion resources that are more than adequate for the Psyche mission, and can easily accommodate the Psyche payloads. The Psyche spacecraft is thus a stripped-down version of the 1300 satellite bus from SSL with the large telecommunications payload removed and with some thermal control enhancements to support the range of solar distances (1.0 to 3.3 AU). This SEP Chassis is then re-populated with deep space avionics and flight software from JPL. Table 4 summarizes the organizational responsibilities for the various spacecraft subsystems. Table 5 provides a comparison of the Psyche mission's needs, relative to the typical capabilities of SSL's 1300 commercial satellite bus.

As shown in Figure 10, the Psyche spacecraft structure is a rectangular panel-box construction, supported by a core central cylinder made of graphite composite material. The modular xenon tank assembly, consisting of seven identical 82-liter tanks, fits inside the central cylinder. This assembly provides an optimal configuration for the thermal control of the xenon propellant, providing a unified thermal mass with common thermal blanketing that surrounds all of the tanks and the central cylinder. Spacecraft components with rigid mounting requirements are attached to the outside of the central cylinder; other components reside on one of the rectangular panels. The central cylinder and the horizontal deck panels provide the primary load path from the mounted components to the launch vehicle adapter. The structure satisfies the launch load requirements for all of the medium-performance launch vehicles that are offered to Discovery-class missions.

Table 4. Organizational responsibilities for Psyche Spacecraft subsystems

Spacecraft Subsystems/Functions	Organizational Responsibility
SEP Chassis: Structure Propulsion Solar Arrays Power Distribution and Storage[1] Thermal Control Attitude Control Sensors & Actuators SEP Chassis Systems Engineering SEP Chassis Integration and Testing	**SSL**
Avionics Telecommunications[2] Flight Software Guidance and Control Algorithms Fault Protection S/C, Payload Systems Engineering S/C, Payload Integration and Testing	**JPL**

[1]JPL provides a low voltage power distribution and switching assembly, which supplies the JPL loads and the payload loads

[2]SSL provides the High Gain Antenna

The spacecraft's xenon tank assembly carries 1064 kg of xenon propellant, which is the only propellant used by the spacecraft. The xenon tank assembly feeds both the gimbaled SPT-140 Hall thrusters, and a set of twelve cold gas thrusters.

Spacecraft power is provided by two solar array wings, with each wing hosting five panels in a cross configuration. Each solar array wing is articulated by a single-axis gimbal, allowing the spacecraft to keep the arrays sun-pointed while thrusting in a variety of attitudes.

The Psyche spacecraft is three-axis stabilized, using commercially available star trackers and gyros for inertial attitude and rate measurements. Four reaction wheels, mounted in a pyramid configuration, are the primary means of attitude control. The spacecraft also carries a 4-pi steradian sun sensor configuration and cold gas thrusters, which can be used if necessary to achieve and maintain a sun-pointed safe mode.

Table 5. Comparison of key attributes between Psyche and typical SSL GEO comsat

Attribute	Typical SSL GEO S/C	Psyche Spacecraft
Dry mass	3500 kg	<1400 kg
Payload mass	1100 kg	<70 kg
Payload/bus power dissipation	8400 W	Up to 1000W
BOL power @ 1 AU	19 kW	19 kW
Chemical propellant load	2000 kg	0 kg
Xenon propellant load	200 kg	1064 kg
Time to reach destination	30 days	3.5 years
Total mission lifetime	15 years	5 years

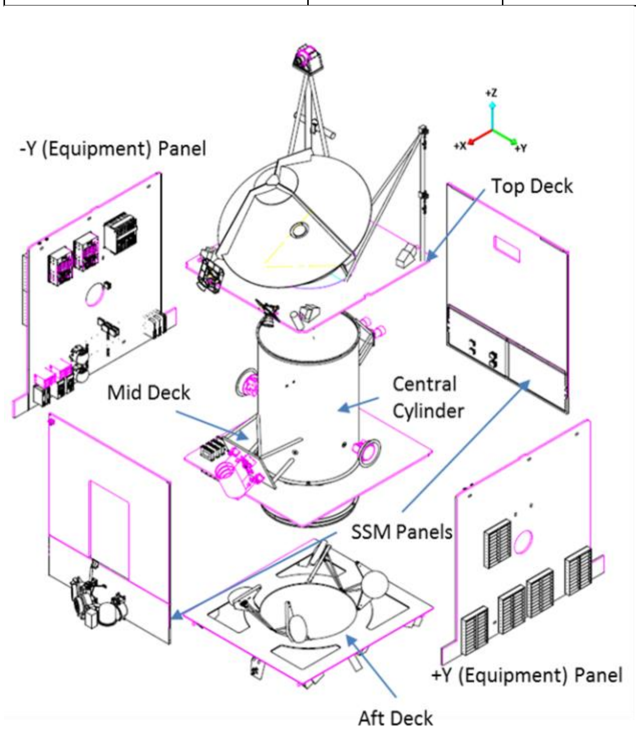

Figure 10. Psyche Spacecraft structural configuration, expanded view

The Psyche spacecraft uses an X-band Small Deep Space Transponder (SDST) to communicate with the Deep Space Network (DSN). The spacecraft supports X-band uplink at rates of up to 2 kbps via a 2m fixed High Gain Antenna (HGA), or via a network of three body-mounted Low Gain Antennas which are oriented to provide 4-pi steradian uplink coverage. The spacecraft uses a 100 W Traveling Wave Tube Amplifier (TWTA) to enable downlink rates of 180 kbps via the HGA at over 4 AU from Earth. The spacecraft can also downlink via a selected LGA, which ensures a downlink data rate of at least 10 bps in safe-mode at over 4 AU from Earth.

The core of the spacecraft's Command and Data Handling (C&DH) subsystem features a JPL-designed compute element, hereafter referred to as the Psyche Compute Element (PCE). There are two block-redundant PCEs, each with a 3U RAD750 PowerPC processor and 4 GB of nonvolatile flash memory. Each PCE interfaces with the SEP Chassis components through an SSL-heritage RS-485 router. Each PCE also provides serial interfaces to the science instruments, and MIL-STD-1553 interfaces to the X-band SDST and the DSOC flight terminal.

During the five-year Psyche mission, the spacecraft avionics are expected to receive a maximum radiation dose of 8 krads (RDM of 2) behind the standard 100-mils of aluminum. SSL typically qualifies all of their SEP Chassis components for ≥ 100 krad, and JPL will use parts that are tolerant to at least 20 krads.

Figure 11 illustrates the integration & test (I&T) flow for the Psyche spacecraft. SSL would assemble and test the SEP Chassis at their Palo Alto production facility, just as they would assemble and test the constituent elements for any other 1300 satellite bus. SSL plans to use their heritage compute element and electrical ground support equipment (EGSE) to test the aliveness and connectivity of their electrical systems. In addition, JPL would bring an engineering model Psyche Compute Element (PCE) to SSL for a few weeks during SEP Chassis I&T, for early interface testing to demonstrate end-to-end data flows.

The bulk of the SEP Chassis I&T activity occurs in Palo Alto during calendar 2020. After completion of SEP Chassis I&T (including solar array installation and deployment), SSL plans to ship the SEP Chassis to JPL in the spring of 2021. The flight PCEs, the deep space telecom equipment, the science instruments, and the DSOC flight terminal would all be installed at JPL. Powered-on functional and performance testing of the flight vehicle would then commence at JPL, in the summer of 2021. Flight vehicle powered-on testing would thus be synergistic with all of the testbed activity (the system testbeds are at JPL), and with preparations for mission operations (JPL manages and conduct mission operations). All of the system-level environmental tests (vibration, acoustics, shock, EMI/EMC, thermal vacuum testing, etc.) are planned to be performed at JPL, starting in fall 2021. Xenon loading also occurs at JPL, shortly before the spacecraft is shipped to the launch site in the spring of 2022.

B. Spacecraft Subsystems

Baseline Power Subsystem

Psyche's power needs would be provided by twin, five-panel solar arrays with 75 m^2 total area. These arrays produce 19.2 kW at 1.0 AU under AMO conditions, and 2.4 kW at the maximum expected heliocentric range of 3.3 AU. The arrays would provide more power than can be consumed by the spacecraft bus and SEP thrusting until a range of about 2.1 AU. The cells are triple-junction ZTJ

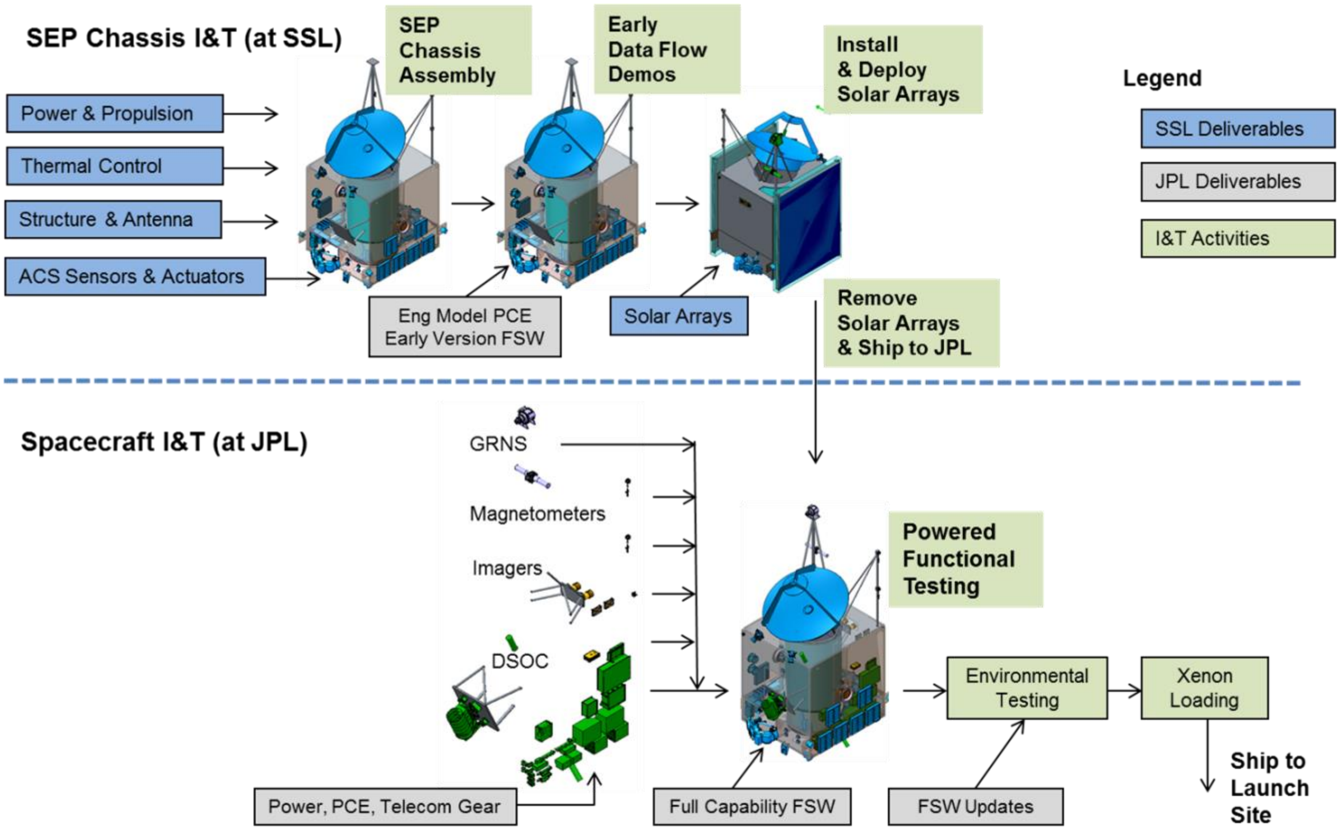

Figure 11. JPL's deep-space flight subsystems are integrated onto an SSL SEP chassis to build a low cost-risk Discovery-class SEP spacecraft

cells provided by SolAero [40] with an AM0 efficiency of 29.5%. There would be binning of the cells by their Low Intensity Room Temperature (LIRT) performance, as a proxy for Low Intensity Low Temperature performance at 3.3 AU. The binned cells would then be selected to create strings of equal voltage. Lower performing cells need not be screened out as the power margin from the arrays, retains a comfortable 36% margin. The cells use twisted wiring and are laid out to minimize the magnetic moments in support of the magnetometer instrument. Each array structure is a rigid graphite composite which is rotated by single axis solar array drive actuators with slip rings for up to 40 circuits.

The original Psyche spacecraft design had four panel arrays, which was optimum when considering only the cost to construct the spacecraft and the original 2023 launch date. When operations cost were considered and the launch date moved to 2022, analysis showed it had become cost effective to use a larger array in order to provide more power to the SEP system, thereby arriving at Psyche quicker and completing mission the earlier.

Because the SPT-140 efficiency and Isp increase with increasing input power [41], Psyche needs to maximize the power available from the solar array when thrusting. This would be accomplished by using array steering – the spacecraft is rotated about the in-use thruster until the solar array axis is perpendicular to the sun line. The solar array gimbals then turn the cells normal to the sun. Non-thrusting modes require less power and the attitude can be less constrained.

The power available for thrusting is the solar array power taken at EOL conditions, subtracted by the bus power (including contingency and 30% margin). To accurately fly to a planned trajectory, the thruster power is set in advance and will not vary with real-time power conditions. Sometimes, transient increases in spacecraft bus power consumption, combined with the static thrusting power, could push the total system power need above what the arrays can provide. In these cases, the extra load would be taken up by the battery.

The power system architecture, shown in Figure 12, is split with most of the hardware and functionality supplied by SSL, and the rest from JPL. One challenge with deep-space solar arrays, is that the array voltage increases as the heliocentric range increases. To manage this, we plan to use the SSL Power Control Unit (PCU). The PCU accepts array input voltages as low as 60 volts, and would boost them to approximately 100 volt for output. The arrays would be strung so that the maximum voltage at 3.3 AU rises to 100 volts, leading to efficient power processing when the power is needed most. Should the array voltage exceed 100 volts, the PCU would shunt the excess. The PCU contains fuses for isolating strings and capacitors to provide extra current for transient events such as the start-up of the SPT-140s.

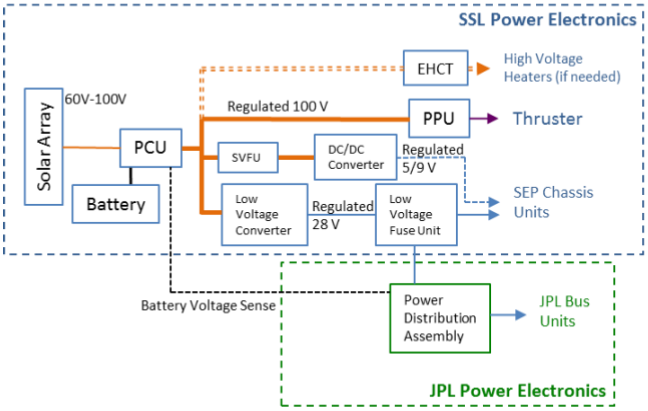

Figure 12. Psyche Spacecraft Power Block Diagram

The PCU routes up to 5 KW of power to the Power Processing Unit (PPU) which provides power to the SPT-140 for thrusting. PCU power is also provided to run the spacecraft, partially by routing power to a JPL-provided Power Distribution Assembly (PDA) which sends unregulated ~30 volt power to the JPL-supplied telecom equipment, computer, the imager, GRNS and DSOC. All the remaining avionics are provided by SSL. Some are powered off a regulated 5, 9 or 31 volt power supplies which are themselves fed from the PCU.

Finally, the PCU routes power to charge a 144 AHr GS Yuasa battery which is controlled by a Smart Battery Tray, all of which are part of the SSL standard EPS 2.0 system. Providing additional operational flexibility, this architecture allow the battery to provide power to the PPU for SEP operation during eclipses at the asteroid.

Other than the battery, the power system is single-fault tolerant, block redundant with the SSL and JPL sides have separate fault-containment regions.

Propulsion Subsystem

The Psyche propulsion system is responsible for interplanetary cruise from Earth to Psyche, orbit maintenance at Psyche, momentum offloading from the reaction wheels, launch vehicle tipoff control, and safe mode operations (e.g. detumble, sun-pointing, etc.).

Primary propulsion is provided by the flight-qualified SPT-140 electric propulsion system, scheduled for first flight on an SSL spacecraft in 2017 [42]. The SPT-140 thrusters, shown in Figure 13, provide higher thrust levels and lifetime than the SPT-100 system successfully used on over 30 SSL spacecraft since 2004, at about three times the power consumption. Nearly all of the components of the SPT-140 system are unmodified versions of those used in the commercial geostationary spacecraft [43]; the major difference being the xenon flow controller (XFC) which requires a greater throttle range for Psyche than the XFC-140 can provide. Instead, the Psyche XFC utilizes the flight-proven Moog Proportional Control Flow Valve (PFCV). A redesign of the flow control tray is required to drive the PFCV; otherwise the PPU is unchanged [44]. A suite of seven heritage 82-L propellant tanks, ganged together, store the Psyche xenon load.

Although the spacecraft is equipped with four SPT-140 thrusters (three for propellant throughput, one for redundancy), only a single one operates at any given time. Additionally, the thruster must accommodate a greater throttle range than in the commercial application because the spacecraft power decreases as it travels to the asteroid. A series of tests, including extended duration testing on the life test unit, have been conducted to demonstrate the capability necessary for Psyche [44]. Two Power Processing Units (PPUs) are fully cross-strapped to enable operation of a single PPU with any of the four thrusters.

Figure 13. The Psyche mission concept utilizes the SPT-140 thruster

A xenon cold gas propulsion system augments the SPT-140 electric propulsion system to provide higher thrust levels for some non-deterministic thrusting and all safe mode operations. Xenon was chosen as the propellant even though it has a low specific impulse in this application in order to simplify the system; the cold gas system piggybacks off of the xenon tank manifold and shares the propellant margin with the EP system. The system is composed of flight-proven hardware with the exception of the thrusters which require a simple modification for xenon use. Twelve thrusters in redundant banks of six are used, each controlled by an individual valve to provide coupled thrust. A series-redundant high-flow regulator supplies gas to the thrusters.

Attitude Determination and Control Subsystem

The Psyche spacecraft Attitude Determination and Control System (ADCS) is responsible for attitude estimation and control throughout the mission. Proposed ADCS capabilities include nadir and off-nadir pointing during science observations, inertial pointing of the science instruments for calibrations, Earth pointing of the body-fixed high gain antenna and DSOC payload to support communications, as well as time-profiled inertial pointing of the EP thrust vector during cruise thrusting, science orbit transfers and for orbit maintenance. Additionally, ADCS would implement control laws for solar array pointing, for monitoring and managing the stored Reaction Wheel Assembly (RWA) momentum, and for pointing the SEP gimbals. To support spacecraft "safe mode", ADCS would also provide functions for detumble, sun acquisition and Sun-referenced attitude control using either RWAs or cold-gas thrusters.

Inertial attitude estimation would be accomplished using data from redundant Jena-Optronik star trackers and Asterix fiber optic gyros blended in an onboard Kalman filter. Sun-referenced attitude estimation would use data from gyros and a set of Adcole pyramid-type coarse sun sensors (CSS) that provide redundant, near 4π steradian coverage. Primary attitude control would use a pyramid configuration of four Honeywell HR 16-100 Reaction Wheels to give redundant, 3-axis control using three or four wheels.

Nominal RWA unloading and momentum control would be accomplished using torques generated by the EP system. ADCS would use an approach similar to SSL's communications satellites. The RWAs would provide full 3-axis control of the spacecraft while a low-bandwidth momentum control algorithm positions the EP gimbal to direct the thrust vector near the vehicle center of mass (CM). Small offsets to the EP thrust vector would produce torques that allow continuous unloading of two axes of RWA momentum. The remaining axis would be unloaded every few days using short (~15 min) EP-unload burns. Unlike the DS1 and Dawn spacecraft, the Psyche ADCS would not use the EP gimbals for direct attitude control during thrusting [44].

Backup three-axis attitude control would be provided by a 12 thruster cold gas system (CGS). The baseline CGS uses Xenon as propellant to avoid additional tankage and to share the large xenon contingency for EP thrusting. Other cold gas propellants may be considered to raise specific impulse and provide additional thrust. The CGS would also be used to provide emergency RWA unloading capability in the event EP unloading is not available.

The core attitude estimation and control algorithms are expected to have high commonality with those used on the Cassini, SMAP and the Europa Clipper missions. The momentum control algorithms would be developed using high fidelity simulations that includes detailed disturbance models for solar radiation pressure, gravity gradient torque and for "swirl" torque created by the EP thruster.

Avionics Subsystem

The Psyche avionics subsystem consists of a JPL-delivered redundant Psyche Compute Element (PCE) that hosts JPL-delivered flight software, and redundant SSL-delivered Router and Attitude Control Electronics (ACE). The PCE provides cross-strapped command and telemetry interfaces to all instruments via heritage high-speed serial or UART/LVDS physical layers and protocol, and to the PDA, SDST, star tracker, and Inertial Reference Unit (IRU) hardware via redundant 1553 data bus. The Router provides command and telemetry interfaces to the SPT-140 thrusters, the solar array drive, heaters, and various analog and temperature sensors via RS-485. The ACE provides command and telemetry interfaces to attitude control actuators and sensors, including the SPT gimbals and cold gas system, via RS-485.

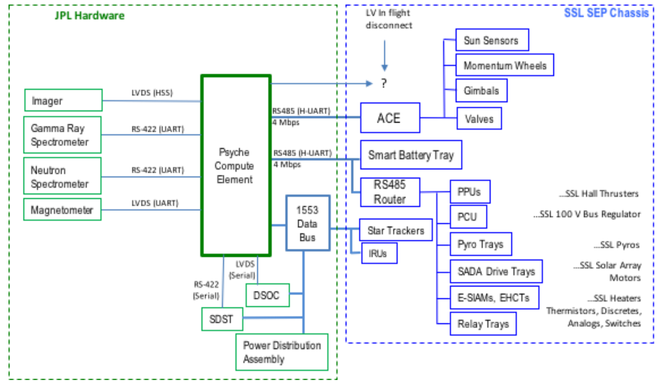

Figure 14. Psyche Avionics Hardware and Interfaces

The PCE contains all flight software in its RAD 750 processor and interfaces with the Router and ACE for control of the SEP chassis hardware via cross-strapped RS-485 interfaces. The PCE provides the and uplink and downlink interfaces for the spacecraft; it receives commands from the telecom subsystem and formats and forwards them to spacecraft hardware for execution, and it collects and stores engineering and science data in nonvolatile flash memory and formats and forwards it to the telecom subsystem for downlink. The PCE also provides housekeeping power, magnetometer +/- 8V power, and boot configuration control. Figure 14 below shows the Psyche avionics hardware and interfaces.

All flight software for the Psyche spacecraft is delivered by JPL, with support from SSL for software related to SEP chassis hardware. Flight software would draw on the new JPL deep space CORE flight software architecture, which is being developed for the Europa Clipper spacecraft and improves on flight software from previous JPL missions (such as SMAP and MSL) by providing time and space portioning. Flight software is layered and modular, with individual device drivers at the lowest levels and subsystem and behavioral executives at the highest level.

Fault Protection

The Psyche spacecraft is single-fault tolerant, meaning that no credible fault can result in failure to achieve mission success. Single fault tolerance is implemented primarily via cold-spare block redundancy, with cross-strapped interfaces between most hardware (including all JPL-SSL interfaces) to provide small fault containment regions and multiple fault tolerance across critical functions.

Fault protection on-board the Psyche spacecraft is implemented in hardware and software. Hardware-based fault protection provides mitigation for low-level faults isolated to a particular hardware unit (e.g., EDAC for memory upsets). Software-based fault protection provides mitigation for function- and behavioral-level faults that span multiple hardware units, require autonomous hardware swaps, require coordination of multiple actions across subsystems, and/or trigger system safe mode (e.g., excess attitude control errors, command loss timer expiration, low battery state of charge). All software-based fault protection is delivered by JPL and implemented via centralized fault protection engine in the PCE.

Due to long communication outages with the ground, the Psyche spacecraft must autonomously detect and respond to faults and achieve a sustainable power-safe, thermal-safe, and communicative safe mode when vehicle health is threatened. If safe mode is triggered, the spacecraft would stop on-board sequences, power-off non-critical hardware, switch to low gain antenna communications, and point the solar arrays to the Sun. The nearly 4pi steradian low gain and Sun sensor coverage means that turn times for communication and Sun-pointing are minimized. In order to minimize cold gas propellant usage, Psyche would primarily use an RWA-based safe mode; Psyche would also have a cold gas-based safe mode for RWA-faults and low power faults. Aside from launch, there are no mission critical events and the Psyche spacecraft is therefore designed to remain in safe mode for up to 28 days, until ground operators can diagnose the fault and recover the spacecraft back to science operations. The mission's missed-thrust margin would account for safe mode occurences during cruise and science operations.

Because Psyche uses a cold-spare architecture, careful consideration has to be taken in the event of a PCE fault. The PDA provides independent detection of a PCE fault and would swap to the backup unit, which can take up to 5 min and during which time there is no software control. All spacecraft hardware, including heaters and actuators, would be safe during this potential flight software outage.

Thermal

Psyche's thermal design is greatly simplified compared to SSL's typical high power GEO communications spacecraft. The elimination of approximately 8 kW of typical thermal dissipation comes from removing several hundred RF components, resulting in the simpler and lighter Psyche spacecraft. The more than 1000 kg of typical RF payload components eliminated consists of: power amplifying Traveling Wave Tube Assemblies (TWTAs), RF switching, signal processing electronics, and supporting payload equipment in addition to complex interconnecting waveguide runs.

As a result, Psyche's thermal loads are comparatively modest, generated by relatively low power bus units, which are easily accommodated on a simplified version of SSL's smallest radiator panel through the removal of thermal control hardware and Optical Solar Reflectors (OSRs). Beyond the dramatically reduced thermal control area, Psyche's thermal design also uses thermal louvers to keep the spacecraft from becoming too cold when far away from the Sun. Replacing the electric heaters typically used on GEO spacecraft, thermal louvers are passive mechanical shutters placed over OSRs that open to provide a clear view to space when warm and close to limit radiative cooling when cold. The louvers used on Psyche are provided by the same vendor that provided the louvers for the Dawn and Juno spacecraft.

SSL and JPL typically use different standards for specification of thermal margin. Figure 15 shows that for flight unit qualification, JPL requires 20 degrees of margin between qualification and Allowable Flight Temperature (AFT) on the high side and 15 degrees of margin between qualification and AFT on the low side. SSL typically requires less margin for its product line of GEO spacecraft. For Psyche, we address this discrepancy by adding enhanced thermal margin for SSL's SEP chassis hardware. The thermal subsystem design would maintain temperatures within the tighter AFT limits shown on the right in Figure 15. This preserves JPL's relatively conservative thermal margins approach without changing qualification temperatures for SSL's heritage production line hardware. With this modification, SSL's SEP chassis thermal environmental requirements are fully compliant with JPL's standard environmental requirements for deep-space missions.

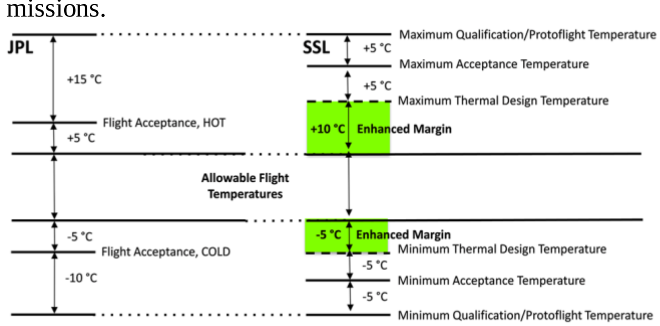

Figure 15. SEP chassis units include enhanced margin, fully compliant with JPL thermal margins for deep space applications

7. CONCLUSION

(16) Psyche is a unique body, composed almost entirely out of metal, the largest of any such known body in the solar system. Potentially an exposed metal core, Psyche may provide answers to fundamental questions on how the planets were formed that cannot be answered through any means other than visiting this world. *Psyche: Journey to a Metal World*, the latest mission concept selected by NASA for implementation as part of the Discovery program, would explore this world for the first time, how it was created, and how its formation relates to other planets in the solar system. The mission, which consists of rendezvous and orbit of (16) Psyche, requires no chemical propulsion, and would represent the first mission to utilize Hall Effect thrusters beyond lunar orbit.

The Psyche mission is enabled by a unique architecture, combining SSL's experience with high power spacecraft and electric propulsion, and JPL's experience building highly autonomous spacecraft for deep space missions. The architecture is built around the concept of a SEP chassis, derived from SSL's GEO product line, combined with a heritage C&DH, telecommunications, and FSW to form the Psyche spacecraft bus. The use of SSL's SEP chassis provides the benefits of flight heritage, a steady product line and low cost-risk. The use of JPL's heritage C&DH and FSW mitigates risk associated with deep space, autonomous operations and fault protection. Together, this architecture provides high heritage while leveraging the strengths of its partner organizations. In combination with the risk reduction tests performed in Phase A, the Psyche mission concept is a design that is mature and provides a firm basis for future development.

ACKNOWLEDGEMENTS

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, and at Space Systems Loral under a contract with the National Aeronautics and Space Administration. The authors would like to thank Viren Patel at Space Systems Loral, and Patrick Peplowski and John Goldsten of the Applied Physics Laboratory at Johns Hopkins University for their contribution to this paper. The authors would also like to thank NASA's Planetary Science Division, NASA's Discovery Program Office, and JPL's Solar System Exploration Program Office for their support of this work.

REFERENCES

[1] Discovery 2014 announcement of opportunity, January 2016, https://nspires.nasaprs.com/external/solicitations/summary.do?method=init&solId=%7BFE7B4C63-873D-63C1-4D15-1D46E2FEA949%7D&path=open

[2] Garner, C., Rayman, M. and Brophy, J. "In-Flight Operation of the Dawn Ion Propulsion System Through Year One of Cruise to Ceres," AIAA Paper 2013-4112, July 2013.

[3] Oh, D., Goebel, D., Polanskey, C., Snyder, S., Carr, G., Collins, S., Lantoine, G., Landau, D., Elkins-Tanton, L., Lord, P., Tilley, S. "Psyche: Journey to a Metal World," AIAA-2016-4541, 52nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Salt Lake City, UT, July 2016.

[4] Oh, D, Goebel, D., Hofer, R. and Snyder, S. "Solar Electric Propulsion for Discovery Class Missions," AIAA Journal of Spacecraft and Rockets, Vol 51, No. 5 (December 2014), pp. 1822-1835. doi: http://arc.aiaa.org/doi/abs/10.2514/1.A32889.

[5] Shepard, M.K., J. Richardson, P.A. Taylor, L.A. Rodriguez-Ford, A. Conrad, I. de Pater, M. Adamkovics, K. de Kleer, J.R. Males, K.M. Morzinski, Radar observations and shape model of asteroid 16 Psyche, Icarus 281, 88–403, 2017.

[6] Kuzmanoski, M., and A. Kovačević (2002), Motion of the asteroid (13206) 1997GC22 and the mass of (16) Psyche. Astron. and Astrophys. 395, L17–L19.

[7] Baer J, Chesley SR, Matson RD. 2011. Astrometric masses of 26 asteroids and observations on asteroid porosity. *The Astronomical Journal* 141: 1-12.

[8] Lupishko, D.F. (2006), On the bulk density of the M-type asteroid 16 Psyche, *Solar System Research 40*, 214-218.

[9] Shepard, M. K., B. E. Clark, M. C. Nolan, E. S. Howell, C. Magri, J.D. Giorgini, L.A.M. Benner, S.J. Ostro, A.W. Harris, B. Warner, D. Pray, P. Pravec, M. Fauerbach, T. Bennett, A. Klotz, R. Behrend, H. Correia, J. Coloma, S. Casulli, A. Rivkin (2008), A radar survey of M and X-class asteroids. Icarus 195, 184–205.

[10] Krasinsky, G.A., E.V. Pitjeva, M.V. Vasilyev, E.I. Yagudina, (2002). Hidden Mass in the Asteroid Belt. *Icarus 158* (1): 98–105.

[11] Hardersen PS, Gaffey MJ, Abell PA. 2005. Near-IR spectral evidence for the presence of iron-poor orthopyroxenes on the surfaces of six M-type asteroids. *Icarus* 175: 141-58.

[12] Shepard, M.K., B.E. Clark, M. Ockert-Bell, M.C. Nolan, E.S. Howell, C. Magri, J.D. Giorgini, L.A.M. Benner, S.J. Ostro, A.W. Harris, B.D. Warner, R.D. Stephens, and M. Mueller (2010), A radar survey of M- and X-class asteroids II. Summary and synthesis. Icarus 208, 221–237.

[13] Matter A, Delbo M, Carry B, Ligori S. 2013. Evidence of a metal-rich surface for the Asteroid (16) Psyche from interferometric observations in the thermal infrared. *Icarus* 226: 419-27.

[14] Asphaug E, Reufer A. 2014. Mercury and other iron-rich planetary bodies as relics of inefficient accretion. *Nature Geoscience* 7: 564-8.

[15] Scheinberg, A., B. Weiss, R. Fu, S. Stanley. G. Schubert, L.T. Elkins-Tanton, Magnetic fields on asteroids and planetesimals, In *Planetesimals: Early Differentiation and Consequences for Planets*, *Ed.* L.T. Elkins-Tanton, B. Weiss, Cambridge University Press, 2016.

[16] Bottke W.F., D. Nesvorný, R.E. Grimm, A. Morbidelli, and D.P. O'Brien (2006), Iron meteorites as remnants of planetesimals formed in the terrestrial planet region. *Nature 439*, 821–824.

[17] Bell III, J.F., A. Godber, S. McNair, M.C. Caplinger, J.N. Maki, M.T. Lemmon, J. Van Beek, M.C. Malin, D. Wellington, K.M. Kinch, M.B. Madsen, C. Hardgrove, M.A. Ravine, E. Jensen, D. Harker,R.B. Anderson, K.E. Herkenhoff, R.V. Morris, E. Cisneros, and R.G. Deen, The Mars Science Laboratory *Curiosity* rover Mast Camera (Mastcam) instruments: Pre-flight and in-flight calibration, validation, and data archiving, *Earth and Space Science, 4,* doi:10.1002/2016EA000219, 2017.

[18] Bell III, J.F., J.N. Maki, G.L. Mehall, M.A. Ravine, M.A. Caplinger, and the Mastcam-Z Science and Engineering Team, Mastcam-Z: Designing a geologic, stereoscopic, and multispectral pair of zoom cameras for the NASA Mars 2020 rover, 3rd International Conference on Instrumentation for Planetary Missions, Abstract #4126, 2016.

[19] Malin, M., J.F. Bell III, W. Calvin, R.T. Clancy, R.M. Haberle, P.B. James, S.W. Lee, P.C. Thomas, and M.A. Caplinger, The Mars Color Imager (MARCI) on the Mars Climate Orbiter, *J. Geophys. Res.*, *106*, 17651-17672, 2001.

[20] Feldman, W., et al., 2004. Gamma-Ray, Neutron, and Alpha-Particle Spectrometers for the Lunar Prospector mission. Journal of Geophysical Research-Planets. 109. http://dx.doi.org/10.1029/2003JE002207.

[21] Boynton, W.V., et al., 2004. The Mars Odyssey Gamma-Ray Spectrometer instrument suite. Space Sci. Rev. 110**,** 37-83. http://dx.doi.org/10.1023/b:spac.0000021007.76126.15.

[22] Evans, L.G., et al., 2001. Elemental composition from gamma-ray spectroscopy of the NEAR-Shoemaker landing site on 433 Eros. Meteorit. Planet. Sci. 36**,** 1639-1660.

[23] Peplowski, P.N., et al., 2011. Radioactive elements on Mercury's surface from MESSENGER: implications for the planet's formation and evolution. Science. 333**,** 1850-1852. http://dx.doi.org/10.1126/science.1211576.

[24] Lawrence, D.J., et al., 2013. Evidence for water ice near Mercury's north pole from MESSENGER Neutron Spectrometer measurements. Science. 339**,** 292-296. http://dx.doi.org/10.1126/science.1229953.

[25] Prettyman, T.H., et al., 2012. Elemental mapping by Dawn reveals exogenic H in Vesta's regolith. Science. 338**,** 242-246. http://dx.doi.org/10.1126/science.1225354.

[26] Prettyman, T.H., et al., 2017. Extensive water ice within Ceres' aqueously altered regolith: Evidence from nuclear spectroscopy. Science. 355**,** 55-58. http://dx.doi.org/10.1126/science.aah6765.

[27] Frank, D., et al., 2016. Extended range of the Lockheed Martin coax Micro cryocooler. Cryogenics. 74**,** 55-58. http://dx.doi.org/10.1016/j.cryogenics.2015.10.002.

[28] Evans, L.G., Peplowski, P.N., Rhodes, E.A., Goldsten, J.O., Starr, R.D., Solomon, S.C., 2017. The MESSENGER Gamma-Ray Spectrometer: Calibration and operations. Icarus. 288**,** 186-200. http://dx.doi.org/10.1016/j.icarus.2017.01.022.

[29] Feldman, W., et al., 2004. Gamma-Ray, Neutron, and Alpha-Particle Spectrometers for the Lunar Prospector mission. Journal of Geophysical Research-Planets. 109. http://dx.doi.org/10.1029/2003JE002207.

[30] Mitchell, D.G., et al., 2013. Radiation Belt Storm Probes Ion Composition Experiment (RBSPICE). Space Sci. Rev. 179**,** 263-308. http://dx.doi.org/10.1007/s11214-013-9965-x.

[31] Evans, L.G., Peplowski, P.N., Rhodes, E.A., Goldsten, J.O., Starr, R.D., Solomon, S.C., 2017. The MESSENGER Gamma-Ray Spectrometer: Calibration and operations. Icarus. 288**,** 186-200. http://dx.doi.org/10.1016/j.icarus.2017.01.022.

[32] Heffern, L.E., Burks, M.T., Lawrence, D.J., Goldsten, J.O., Peplowski, P.N., 2017. Initial Characterization of the GeMini Plus, a High-Resolution Gamma-Ray Spectrometer for Planetary Composition Measurements. 48th Lunar and Planetary Science Conference, Houston, Texas. Abstract 2215.

[33] Lawrence, D.J., et al., 2017. The GeMini Plus High-Purity Ge Gamma-Ray Spectrometer: Instrument Overview and Science Applications. 48th Lunar and Planetary Science Conference, Houston, Texas. Abstract 2234.

[34] Russell, C. T., Russell, C. T., B. J. Anderson, W. Baumjohann, K. R. Bromund, D. Dearborn, D. Fischer, G. Le et al. "The magnetospheric multiscale magnetometers." Space Science Reviews 199.1-4 (2016): 189-256.

[35] Whiffen, G.J., "Mystic: Implementation of the Static Dynamic Optimal Control Algorithm for High-Fidelity, Low-Thrust Trajectory Design," AIAA/AAS Astrodynamics Specialist Conference, Paper No. AIAA 2006-6741, Keystone, Colorado, Aug. 21-24, 2006.

[36] Whiffen, G.J., "Static/Dynamic Control for Optimizing a Useful Objective," United States Patent No. 6,496,741. Issued Dec. 17, 2002, Filed Mar. 25, 1999.

[37] Kennedy, B., M. Abrahamson, A. Ardito†, D. Han, R. Haw, N. Mastrodemos, S. Nandi, R. Park, B. Rush, A. Vaughan (2013), Dawn orbit determination team: Trajectory and gravity prediction performance during Vesta science phases, Paper AAS 2013-345, *23rd AAS/AIAA Spaceflight Mechanics Meeting*, Kauai, Hawaii, Feb. 10-14, 2013.

[38] Parcher, D.W., and Whiffen, G.J., (2011), Dawn statistical maneuver design for Vesta operations, Paper AAS 2011-180, AIAA/AAS *Astrodynamics Specialist Conference*, New Orleans, Louisiana, USA, Feb. 13-17, 2011.

[39] Rayman, M.D., and R.A. Mase (2014), Dawn's exploration of Vesta, *Acta Astronautica 94*, 159–167.

[40] Fatemi, Navid, John Lyons, and Mike Eskenazi. "Qualification and production of Emcore ZTJ solar panels for space missions." *Photovoltaic Specialists Conference (PVSC), 2013 IEEE 39th*. IEEE, 2013.

[41] Hargus Jr, William, et al. *Preliminary performance results of the high performance Hall system SPT-140*. No. AFRL-PR-ED-TP-2000-137. AIR FORCE RESEARCH LAB EDWARDS AFB CA PROPULSION DIRECTORATE WEST, 2000.

[42] Delgado, J. J. , R.L. Corey, V.M. Murashko, A.I. Koryakin, and S.Y. Pridanikov, "Qualification of the SPT-140 for use on western spacecraft," AIAA-2014-3606, 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cleveland, OH, July 28-30, 2014.

[43] Jameson-Silva, K., Delgado, J.J., Liang, R., Lord, P.W., Rotlisberger, L., Torres, M., Tomescu, B., Malone, S.P., Werner, E., and J. Waranauska., "Adaptability of the SSL Electric Propulsion-140 Subsystem for use on a NASA Discovery Class Mission: Psyche", IEPC-2017-181, 35th International Electric Propulsion Conference, Atlanta, GA, October, 2017

[44] Oh, D., Collins, S., Goebel, D., Hart, B., Lantoine, G., Snyder, S., Whiffen, G., Elkins-Tanton, L., Lord, P., Pirkl, Z., Rotlisberger, L., "Development of the Psyche Mission for NASA's Discovery Program", IEPC-2017-153, 35th International Electric Propulsion Conference, Atlanta, GA, October, 2017

[1] Systems Engineer, Project Systems Engineering and Mission Formulation, William.Hart@jpl.nasa.gov
[2] Flight System Manager, Psyche Project, G.M.Brown@jpl.nasa.gov
[3] Senior Engineer, Guidance & Control Formulation and Flight Operations Dept., Steve.Collins@jpl.nasa.gov
[4] Technologist, Natural Space Environments, Maria.De.Soria-Santacruz.Pich@jpl.nasa.gov
[5] Lead Spacecraft System Engineer, Flight Engineering, Paul.Fieseler@jpl.nasa.gov
[6] JPL Fellow, Propulsion, Thermal and Materials Engineering, Dan.Goebel@jpl.nasa.gov
[7] Systems Engineer, Flight Systems Engineering, Danielle.Marsh@jpl.nasa.gov
[8] Psyche Project Systems Engineering Manager, Psyche Project, david.oh@jpl.nasa.gov
[9] Senior Engineer, Electric Propulsion Group, Steve.Snyder@jpl.nasa.gov
[10] Senior Systems Engineer, Payload Systems Engineering, Noah.Warner@jpl.nasa.gov
[11] Principal Engineer, Outer Planets Mission Design Group, Gregory.Whiffen@jpl.nasa.gov
[12] Director, School of Earth and Space Exploration, ltelkins@asu.edu
[13] Professor, School of Earth & Space Exploration, Jim.Bell@asu.edu
[14] Principal Professional Staff, Johns Hopkins University Applied Physics Laboratory, David.J.Lawrence@jhuapl.edu
[15] Deputy Program Manager, Psyche Program, Peter.Lord@sslmda.com
[16] Power Systems Engineer, Systems Engineering, Zach.Pirkl@sslmda.com

BIOGRAPHY

William Hart *is a member of the Project Systems Engineering and Formulation section at NASA's Jet Propulsion Laboratory, and a member of the Psyche Systems Engineering team. From 2013 to 2016, he served as Principal Bus Engineer for Space Systems Loral (SSL), leading bus design efforts for a variety of commercial and government new business proposals. From 2007 to 2012, he held the position of lead systems engineer for electric propulsion at SSL, and was responsible for the design, development, integration and testing of electric propulsion systems on fifteen geostationary communications satellites. He received his B.S. from the University of Notre Dame in Mechanical Engineering, and his M.S. and Ph.D. in Aeronautics and Astronautics from Stanford University.*

G. Mark Brown *has been with the Jet Propulsion Laboratory (JPL) since 1987, and is presently the Flight System Manager for the Psyche Project. He was previously the manager of JPL's Systems Engineering & Formulation Division, overseeing the Laboratory's systems engineering activities for many advanced concepts and many flight projects. Mark is a JPL Principal; in his two most recent flight project assignments, Mark was the Project Systems Engineer and Engineering Technical Authority for the Dawn Project, and the Project V&V engineer for the Spitzer Space Telescope. Mark is also an experienced fault protection engineer who led the development of autonomous fault protection systems for several JPL missions. Mark holds B.S. and M.S. degrees in Aeronautics and Astronautics from the Massachusetts Institute of Technology, and a M.S. in Systems Management from the University of Southern California.*

Maria de Soria-Santacruz Pich *received a Ph.D. in Aeronautics and Astronautics from MIT in 2014. During 2014 she was a Postdoctoral Scholar at UCLA working on the development of an energetic particle detector for the ELFIN satellite and on the analysis of Van Allen Probes data. She joined JPL in 2015, where she has worked on the definition of space radiation environments, she has supported radiation analyses and testing for multiple instruments, and she was a member of the PDP development team. In 2017, she joined the Psyche project as a Payload Systems Engineer for the magnetometer instrument. Her interests include space environments, particles and fields instrumentation, and space systems.*

Paul Fieseler *is the Lead Spacecraft Systems Engineer for the Dawn mission and a member of the Flight Engineering group at JPL. He holds a MS in Aerospace Engineering from the University of Southern California (2000) and a BS in Engineering Physics from the University of Kansas (1988). He has contributed to robotic missions such as Galileo, Mars Odyssey and Cassini, and human missions as a Space Shuttle Mission Controller.*

David Oh *is Project Systems Engineer for "Psyche: Journey to a Metal World," a mission that will use EP to explore the largest metal asteroid in the solar system. David is a senior systems engineer at NASA's Jet Propulsion Laboratory and was Lead Flight Director of NASA's Curiosity Mars Rover. He led the teams that successfully flew the rover to Mars in 2012 and led the cross-cutting systems engineering team that designed, tested, and delivered the rover's core avionics, thermal, and communications systems. He received a Sc.D. in Aeronautics and Astronautics from MIT in 1997.*

Linda T. Elkins-Tanton *is the director of the School of Earth and Space Exploration at Arizona State University and the Principal Investigator of the Psyche space mission. Her research is on the formation of rocky planets and the relationships between planets and life. She has led four field expeditions in Siberia and worked in the Sierra Nevada, the Cascades, and Iceland. Elkins-Tanton received her B.S., M.S., and Ph.D. from MIT. Before her Ph.D, she spent several years writing business plans. She was on the MIT faculty, culminating as Associate Professor of Geology, before accepting a directorship at the Carnegie Institution for Science. In 2014, she moved to ASU. Elkins-Tanton is a twotime National Academy of Sciences Kavli Frontiers of Science Fellow. She was awarded the Explorers Club Lowell Thomas prize and named the 2013 Astor Fellow at Oxford University.*

Jim Bell *is a professor in the School of Earth & Space Exploration at Arizona State University, and is President of the Board of Directors of The Planetary Society. He is an active astronomer and planetary scientist who has been involved in solar system exploration using the Hubble Space Telescope, Mars rovers, and orbiters sent to Mars, the Moon, and several asteroids. His research focuses on the use of remote sensing imaging and spectroscopy to assess the geology, composition, and mineralogy of the surfaces of planets, moons, asteroids, and* *comets. He is also an author of popular science books related to space exploration, including "Postcards from Mars", "The Space Book", and "The Interstellar Age."*

***David J. Lawrence** is the lead for the Psyche GRNS. David has extensive experience in the development and use of spaceflight instrumentation, with a specific focus on planetary gamma-ray and neutron spectrometers, and is author or co-author on over 150 peer-reviewed publications. He has worked on various spaceflight missions including NASA's Lunar Prospector, Deep Space 1, Mars Odyssey, MESSENGER, and Dawn missions. He received a B.S. in physics and mathematics from Texas Christian University in 1990, and an M.A. and Ph.D. in physics from Washington University in Saint Louis in 1996.*

***Peter Lord** is currently SSL's Deputy Program Manager for Psyche. He received a B.S in Engineering from Syracuse University in 1984 and a M.A in Liberal Arts from Stanford University in 2002. A three-decade veteran of the commercial communication satellite industry, Peter holds multiple patents for antenna technology. His experience includes the development of entirely new types of commercial space applications, most notably as Lead System Mechanical Engineer for the inaugural Sirius Satellite Radio Constellation. Peter's experience with SEP began in 2002 as the system mechanical engineer for MBSAT, the first SSL spacecraft to employ EP, which began service in 2004. Mr. Lord specializes in the development of Advanced SEP Capabilities and Programs based on SSL's success over the past decade flying Hall Effect thruster propulsion systems on 26 spacecraft. Mr. Lord served as both Systems Lead and Proposal Manager for SSL's NASA study "Adapting Commercial Spacecraft for the Asteroid Redirect Mission" and as SSL's Phase A Program Manager for the Psyche SEP chassis.*