An Approach to Magnetic Cleanliness for the Psyche Mission

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Abstract— **Psyche is a Discovery mission that will visit the asteroid (16) Psyche to determine if it is the metallic core of a once larger differentiated body or otherwise was formed from accretion of unmelted metal-rich material. The spacecraft will launch in August 2022 and arrive at the asteroid in January 2026. Psyche will carry three science instruments: a gamma ray and neutron spectrometer, a magnetometer, and a multi-spectral imager. Additionally, the spacecraft will host the Deep Space Optical Communications payload, which is a technology demonstration not required to meet Psyche's science objectives. The magnetometer is composed of two identical high-sensitivity magnetic field fluxgate sensors mounted in a gradiometer configuration that enables the rejection of meter-scale stray fields from the spacecraft. The instrument is key to meeting mission objectives since measurements of a strong asteroid remanent magnetic field will unambiguously indicate that (16) Psyche is an iron core.**

The magnetic signature from the spacecraft is the main source of noise for the magnetometer, both for DC and AC magnetic fields. Limiting and characterizing spacecraft-generated magnetic fields is therefore essential to the mission. This is the objective of the Psyche's magnetics control program described in this paper. The first step towards a successful program was to establish a set of magnetic cleanliness requirements directly derived from the magnetometer science performance and Psyche's range of expected fields. Test and modeling efforts of DC and AC fields of spacecraft components were then put in place to characterize and understand the spacecraft fields and enable verification of the cleanliness requirements. In this paper we describe the derivation of these requirements, test and analyses methods, and more generally the processes and procedures that govern the magnetics program for Psyche. The paper concludes with a discussion of the challenges and work to go and a comparison with the magnetic control processes of other missions with similar magnetic cleanliness constraints.

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1. INTRODUCTION

Psyche is a NASA Discovery-class mission that will visit the asteroid (16) Psyche to determine if it is the metallic core of a larger differentiated body or otherwise was created by a slow accretion of metal-rich material. The mission is led by Arizona State University (ASU) while the Jet Propulsion Laboratory (JPL) provides management and systems engineering support as well as avionics, telecommunications, and power distribution deliverables [1], [2]. The rest of the subsystems including structures, thermal, propulsion, and power are delivered by Maxar Technologies constituting what is called the solar electric propulsion (SEP) chassis. Psyche carries three science instruments including a gamma ray and neutron spectrometer (GRNS), a magnetometer, and the Psyche multispectral imager. Additionally, Psyche hosts the deep space optical communications (DSOC) payload, which is a technology demonstration not required to meet Psyche's science objectives.

Psyche is expected to launch in August 2022 and arrive at the asteroid in January 2026. The mission is enabled by SPT-140 hall thrusters to rendezvous and orbit (16) Psyche. The spacecraft will orbit the asteroid in a series of four progressively lower circular orbits shown in Figure 1. This strategy enables progressive characterization of the shape and gravity field of (16) Psyche at each orbit altitude, which informs the design of subsequent lower orbits and transfers. Additionally, each orbit provides optimal conditions for a specific science investigation.

The Psyche magnetometer is a UCLA-built instrument with science investigation leadership from MIT. The magnetometer's role is to help determine if (16) Psyche is a core of a differentiated body by sensing an ambient field intensity in the spacecraft environment of up to 10,000 nT in 3-axes. If (16) Psyche is a core, it may have a strong remanent magnetic field. In particular, the magnetometer experiment is designed to be able to detect a minimum dipole moment of $2x10^{14}$ A-m^2 by the end of the mission. Data are digitized to provide ±0.1 pT and ±10 pT resolution in two selectable dynamic ranges of ±1,000 nT 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 has an intrinsic noise resolution of 0.01 nT/√Hz at 1 Hz for the low range, and the instrument collects data with a sampling rate of 16 Hz during all science orbits. The Psyche magnetometer is composed of two identical high-sensitivity three-axis magnetic field sensors of the fluxgate type mounted in a gradiometer configuration that enables the rejection of meter-scale stray fields from the spacecraft. The intra-instrument harness is routed along a fixed boom to connect each sensor with its electronics unit (one independent electronics unit per sensor). The magnetometer powers on during initial checkout and remains on for the rest of the mission. Although the instrument is powered on continuously, it is not expected to acquire science-grade data while thrusting or during DSOC operations (these assemblies will both be unpowered while the instrument is taking calibration or science data).

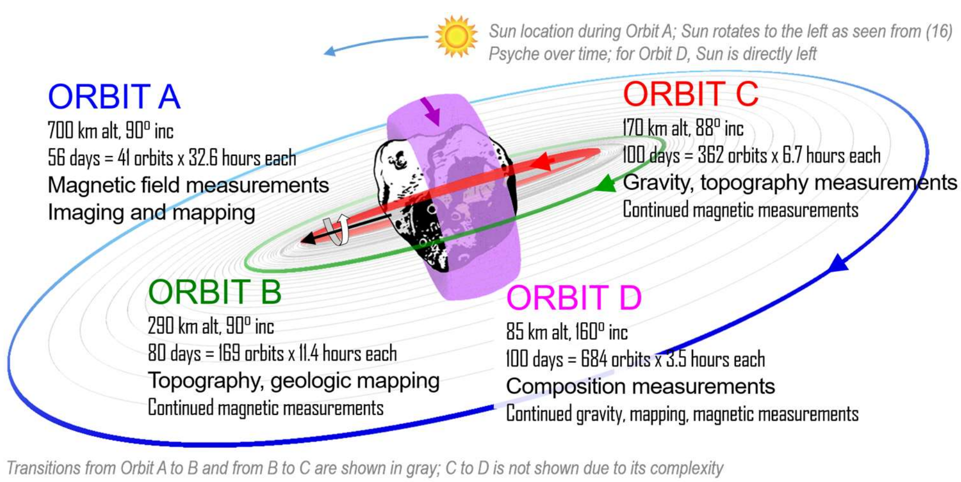

Figure 1. Psyche Orbital Operations

The magnetometer sensor, electronics unit, and their configuration on the spacecraft are shown in Figure 2. The inboard and outboard magnetometers are 1.45 m and 2.15 m from the base of the boom, respectively.

The magnetometer is susceptible to noise from both the DC and AC magnetic fields generated by the spacecraft. Project requirements are in place to limit spacecraft-generated fields as to guarantee that science objectives are met. Some of these requirements are driven by the capability of the gradiometer configuration, which is a technique key to differentiating spacecraft-generated fields from the asteroid magnetic signature. Section 2 carefully describes these requirements and their rationale, and Section 3 addresses Psyche mission's approach to magnetic cleanliness. Section 4 describes verification and validation (V&V) of the requirements, while specific test and analyses methods are described in Section 5. Section 6 provides an overview of special considerations for spacecraft assembly, integration, and test. Finally, the paper concludes with a summary and discussion of findings and open issues.

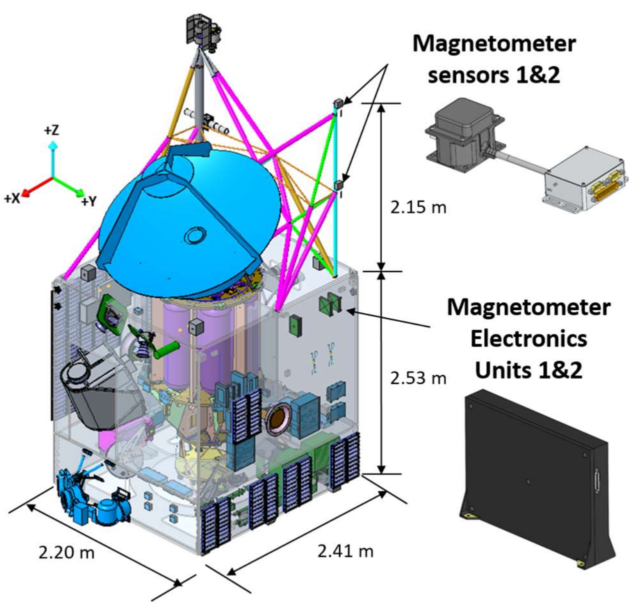

Figure 2. The configuration of the magnetometer sensors and their electronics units on the Psyche spacecraft

2. DRIVING REQUIREMENTS

The spacecraft magnetic cleanliness requirements flow directly from magnetometer science performance requirements. Specifically, the magnetometry science investigation requires a ground-reconstructed uncertainty for a single measurement of the ambient magnetic field at (16) Psyche to be smaller than +/-1.5 nT or 3% of the measured field (whichever is larger) 3σ per axis for measurements below 1,000 nT. This uncertainty is sub-allocated between its different sources, which include the magnetometer intrinsic noise and the uncertainty in the knowledge of spacecraft-generated fields. Specifically, the uncertainty in the knowledge of spacecraft-generated fields that enables a successful magnetometer science investigation is +/-0.4 nT 3σ per axis, which drives the allowable spacecraft fields (i.e., the magnetic cleanliness requirements).

The calculation of the allowable spacecraft fields that correspond to the uncertainty above takes advantage of the gradiometer configuration of the magnetometer sensors (see Appendix A for a description of the gradiometer technique and its application to the derivation of magnetic cleanliness requirements). This results in the magnetic cleanliness requirements in four frequency bands:

- DC magnetic fields: Spacecraft-generated magnetic fields shall not exceed 30 nT as measured at the location of the inboard magnetometer sensor. This requirement is driven by the capability of the gradiometer technique to reject DC fields. Although DC fields are expected to be mainly rejected using solar wind-based calibrations (see Section 5 for a brief description of these), the spacecraft may not have access to the solar wind at the lower orbits (where the asteroid's field may be stronger). Therefore, at these lower orbits, the gradiometer technique may be used instead to reject spacecraft-generated DC noise.

- 10^{-5} Hz to 0.1 Hz magnetic fields: Spacecraft-generated magnetic fields shall not exceed 2.1 nT in this frequency range as measured at the location of the inboard magnetometer sensor. The capability of the gradiometer technique drives again this requirement. This frequency range is of special interest because (16) Psyche's field variation is expected to be in this range as seen from the orbiting spacecraft.

- 0.1 Hz to 16 Hz magnetic fields: Spacecraft-generated magnetic fields shall not exceed 1 nT in this frequency range as measured at the location of the inboard magnetometer sensor. The Psyche magnetometer is required to be single fault tolerant, which is the driver for this requirement. Specifically, this requirement allows the magnetometer investigation to meet the science performance requirements in a scenario where the outboard magnetometer sensor is lost. The lower end of the frequency range is constrained by the capability to measure spacecraft assemblies on the ground, while the upper frequency limit corresponds to the instrument sampling frequency.

- >16 Hz magnetic fields: Spacecraft-generated magnetic fields shall not exceed the curve shown in Figure 3 as measured at the location of the inboard magnetometer sensor. This curve was derived empirically and it is the result of aliasing of magnetic noise into the instrument bandwidth (16 Hz).

The requirements above are in line with those from other magnetometer missions like Juno, which required the spacecraft-generated magnetic field to remain below 2 nT for

DC fields and 0.5 nT for variable fields as measured at the location of Juno's magnetometer sensors (mounted at the extreme of one of the 9 meter solar arrays). Similarly, Juno specified a spectrum of allowable fields between 30 Hz and 100 kHz in line with Psyche's specification in Figure 3.

In addition to the not-to-exceed spacecraft fields above, a set of requirements were placed on the decay of the spacecraft-generated magnetic fields between inboard and outboard magnetometer sensors, which are also driven by the capability of the gradiometer. Specifically, the decay factor between inboard and outboard magnetometer sensors is 1.5 for DC fields, 1.3 between 10^{-5} Hz and 0.1 Hz, and 2.0 between 0.1 Hz and 16 Hz. The gradient requirements will be verified by analysis, while requirements on not-to-exceed magnetic fields will be verified by a combination of tests and analyses. A detailed description of the verification process can be found in Section 4.

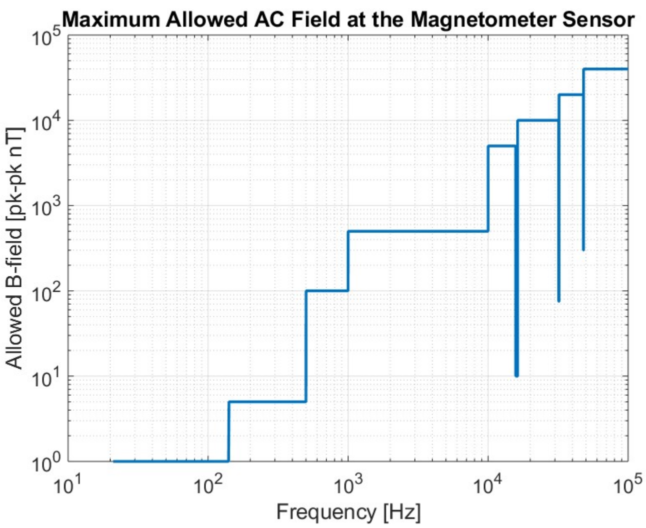

Figure 3. >16 Hz Magnetic Cleanliness Requirement

3. APPROACH TO THE MAGNETIC CLEANLINESS PROGRAM

The purpose of the Psyche magnetic cleanliness program is to ensure that science-grade magnetic field data can be collected during cruise calibration periods as well as in orbit around (16) Psyche. Responsibility for magnetic cleanliness is shared among cross-cutting teams at all of the partner institutions. Figure 4 provides a graphical representation of the general work and responsibility flow. Each box contains an activity and a responsible party. In almost all cases, there are responsible team members at multiple institutions. The Psyche Magnetic Control Review Board (Psyche MCRB) includes team members from each responsible partner institutions. The Psyche MCRB serves as the forum for coordination and oversight of the implementation of the Psyche magnetic cleanliness program.

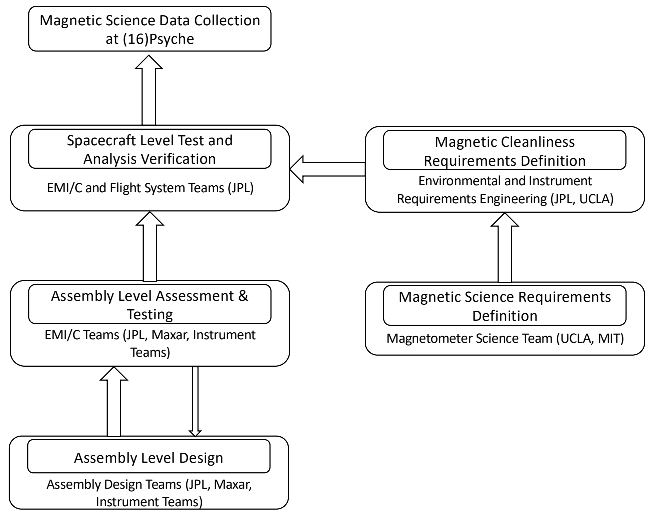

Figure 4. Psyche Magnetic Cleanliness Program workflow chart from science requirements to data collection. Each responsible team has a seat on the Psyche Magnetic Control Review Board (MCRB)

Looking at the right side of Figure 4, the magnetic science requirements are defined by science team members and are informed by previous missions with similar magnetometers (e.g. Juno, MAVEN, and InSight). These science requirements, combined with intrinsic instrument functional requirements are translated into overall magnetic cleanliness requirements (described in Section 2) for the Psyche spacecraft by instrument and environmental engineering teams at UCLA and JPL, respectively. Magnetic cleanliness requirements for the inboard and outboard magnetometer sensor locations are therefore directly derived from the science needs and they are specified in the Psyche Environmental Requirements Document, which contains all environments relevant to the Psyche mission (launch environments, thermal environments, electromagnetic interference and compatibility, magnetics, etc). Once the maximum allowable background field produced by the spacecraft is specified in the requirements, a set of allocations is appointed to each assembly. With a few exceptions, assembly magnetic field allocations are bookkept as guidelines while the overall spacecraft allowable magnetic fields are defined as hard requirements. With this approach, the MCRB can trade off parameters like assembly magnetic field strength, locations on the spacecraft, and unit orientation to most efficiently meet overall magnetic field requirements at the sensor locations. As assembly level assessment and testing is completed, the magnetic field allocations are updated and/or validated. Once all the planned assessments are complete, then, a verification at the spacecraft level can be completed via analysis and test.

The Psyche implementation paradigm specifies that the SEP chassis provided by Maxar will maintain as much heritage from Maxar's long history of successfully building and flying geo-stationary telecommunications satellites. Consequently, a large majority of the assembly level hardware has no history of magnetic cleanliness. With few exceptions, assemblies are accepted as-is and assessed for magnetic cleanliness. New hardware designers from all partner institutions can borrow from magnetic cleanliness best-practices outlined in the Psyche magnetics control plan.

Hardware designers for each Psyche assembly are responsible for delivering results from magnetics testing or analysis of their assemblies. These results are assessed for magnetic cleanliness by the electromagnetic interference / compatibility teams. Testing can be conducted at JPL or Maxar facilities, with magnetic assessment hardware on loan from JPL. High-risk items identified as potentially magnetically noisy sources (e.g. motors, current switches, soft-magnetizable material) are preferentially assessed as early as possible since they are likely to negatively affect the overall spacecraft cleanliness. The results of each assessment are reported to the Psyche MCRB and are integrated into the magnetic mapping model.

In cases where the magnetic assessment shows a particularly noisy assembly mitigations can be suggested to the Psyche Project. Mitigating design changes are intended to be as minimal as possible (e.g. addition of magnetic shields or compensation magnets, reorientation of sub-assemblies).

4. Requirements Verification Approach

As noted above, we need to understand and limit spacecraft-generated fields to meet the magnetometer science requirements. DC and AC magnetic models of the spacecraft have been developed to estimate spacecraft-generated fields as seen by the magnetometer sensors, which take inputs from magnetics tests of each spacecraft assembly relevant to each frequency range (see Section 5 for a description of these models, tests, and relevant assemblies). These models are used to verify the magnetic cleanliness requirements listed in Section 2. The resulting magnetic field uncertainty from spacecraft-generated fields together with simulations of potential (16) Psyche magnetic field configurations when embedded in the solar wind [3] are used to ensure that the magnetometer science goals are met.

DC and AC models need to be validated prior to being used for requirement verification, where validation in this instance means proving that the model reflects reality. Validation of these models takes many forms, including (in order of rigor):

- Face validation: an evaluation of the plausibility of model results by subject matter experts
- Peer review: a review of the model itself, e.g., equations and coding
- Functional decomposition and test: piecewise testing of model components, e.g., inject test inputs and examine outputs
- Empirical validation: comparison of model results with data from the test of a real system. While this is the preferred method, cost and feasibility are limiting factors.

The DC model is validated by a combination of peer review, functional decomposition and test, and empirical evaluation, while the AC model is validated by a combination of face validation and peer review. Specifically, a system level test of the spacecraft during spacecraft integration and test will be used to partially validate the DC model. At a minimum, this test will measure magnetic fields from the entire spacecraft in a power off configuration, therefore validating the model for magnetic materials but not for current loops. Additionally, assembly-level test results that feed the DC model will provide functional decomposition validation of this model. Finally, the model will go through careful review by subject matter experts and stakeholders from Maxar, JPL, UCLA, and MIT. As for the AC model, its validation mostly relies on peer review and expert evaluation. It is important to note that because the AC model is leveraging some inputs from the DC model (e.g., component location and orientation and operating modes), validation of the AC model relies heavily on the validation of the DC model.

Additionally, the requirement in the range between 10^{-5} Hz and 0.1 Hz will be verified with a separate model of solar array-generated magnetic fields because the solar array is believed to be the main contributor to this frequency range. This model is composed of two sub-models:

1. A model of the magnetic fields due to any current loops from the solar panel wiring (provided by SolAero, the solar array provider) and its routing to the spacecraft power subsystem. This model is developed by JPL electromagnetic compatibility engineers
2. A model of the rotation of the solar array around the spacecraft that takes into account the sun tracking slew rates and that generates fields in this very low frequency range of interest to the magnetometer instrument. This model is developed by the science team at MIT

The first of the models will be validated with a small-scale illumination test of the array, while the second model will be validated via peer review and subject matter expert evaluation.

The verification and validation approach to the magnetic cleanliness requirements is summarized in Figure 5. A detailed description of the test and analysis methods above is provided in the next section.

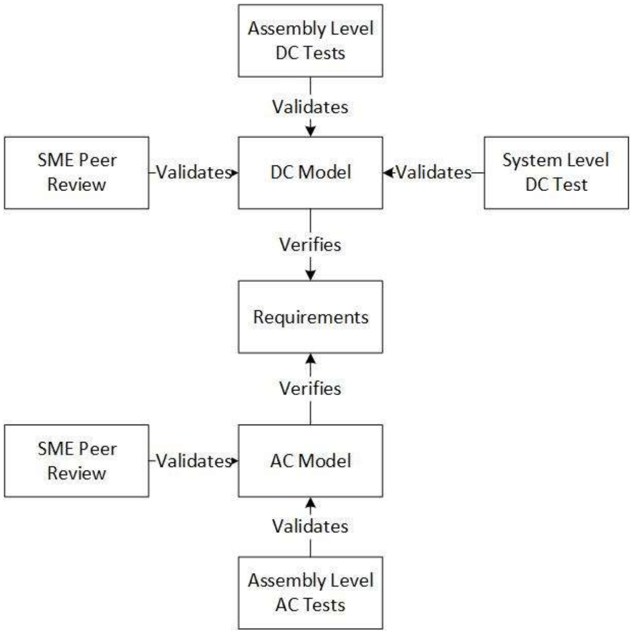

Figure 5 - Magnetic Cleanliness Requirements Verification and Validation

5. TEST AND ANALYSIS METHODS

The Psyche MCRB is responsible for planning and executing the test measurements and analyses to verify the magnetic cleanliness requirements levied on the Psyche spacecraft. Magnetics testing is mostly performed on engineering or qualification units so that any major exceedances can be mitigated with minimal impact on the flight build schedule. Testing is performed by the main hardware developers, Maxar and JPL, at their respective test facilities in Palo Alto and Pasadena, California (see Figure 6). Test and analysis methods vary by domain: DC, very low frequency, and time-varying AC magnetic fields. The test methods employed are tailored to provide the necessary data to analytically verify the various requirement domains. Special tests such as the flight solar panel DC magnetic test will inform analyses in both the DC and very low frequency domains. All test data are processed by JPL for requirements verification, with additional analyses performed by MIT to prepare for in-flight operations.

Figure 6. (Left) JPL Helmholtz coil at used for magnetics testing of EM units. (Right) Helmholtz coil at MAXAR.

DC Magnetics Methods

Generally, all powered and most unpowered assemblies have an intrinsic DC magnetic field. The first step in obtaining a meaningful measurement of these fields is to remove the Earth's magnetic field from the measurement. This is achieved with a three-axis Helmholtz coil measurement system, which can be tuned to generate a magnetic field that cancels that of Earth. Field cancellation is obtained by introducing a current on each axis of the Helmholtz coil. The current flowing through each axis is chosen as to generate a magnetic field that cancels that of Earth in each axis. A fluxgate magnetometer is used to measure the DC fields generated by the assemblies under test. Both magnetometer and assembly under test are placed inside the tuned Helmholtz coil, with the fluxgate sensor positioned one meter away from the unit under test. The magnetic moment of the assembly is determined as follows: First, the unit is mounted on a turntable and spun 360 degrees as the magnetic field and the turntable position angle are recorded during the measurement. Next, the unit's 360 degree measurement rotations are made with the unit oriented in six different angles, providing a detailed mapping of the unit's DC magnetic field. Lastly, the six measurement runs are processed to produce the unit's magnetic dipole moment. At the start of each measurement, the test magnetometer is biased with a neutralizing field so that as the unit under test is rotated, the changes in DC magnetic field as a function of rotation angle are all captured by the magnetometer. Before testing any hardware, the test configuration is verified for calibration using a known magnetic source. The test setup varies in complexity depending on the power configuration of the assembly (some units only need to be tested for magnetic materials while others may have to be tested in different power or operational modes) and the required ground support equipment. It is therefore critical to understand the operational modes of each assembly that are relevant to the magnetometer investigation.

A DC magnetic model of the spacecraft has been developed to integrate the test data from all different assemblies described above and calculate the resultant field at the location of the Psyche magnetometer sensors. The development and maintenance of this model is the responsibility of the MCRB. As new unit data is added, model inputs predict more accurately the field at the magnetometers versus the allowable spacecraft limit, thus paving road for the verification of the DC magnetic cleanliness requirements. To validate the model prediction, tests will be performed on the spacecraft at the system level.

The Psyche DC magnetic model process is a continuation of a well-validated method of tracking the individual DC magnetic contributions of the various assemblies, used in past magnetometer missions with great success. Developed and maintained by the JPL electromagnetic compatibility group, the model starts with a general template, which is then tailored for each project. Each unit of interest is contained as an individual entry in the model. The main inputs per assembly are either the radial field seen at 1 meter or moment per axis (x, y, z), and its location in spacecraft coordinates. The model provides the capability to include x-, y-, and z-coordinate rotations to transform assembly test coordinates into spacecraft coordinates if needed.

The input parameters to the model yield a DC magnetic field as seen by the magnetometer instrument expressed in nanotesla (nT). The three axial DC magnetic fields seen by the magnetometer sensors for each unit entry is root-sum-squared (RSSed) to yield the individual contribution of each unit and it is also summed with all the other assembly contributions. The RSS magnetic field per unit is useful for unit-by-unit evaluation and for understanding the unit contribution as a function of its operational state. However, the sum of all axial magnetic fields from all assemblies is crucial for magnetic cleanliness requirements verification. The RSS of the summed DC fields is what is used to capture the total DC magnetic field produced by the Psyche spacecraft as seen by the magnetometer.

Experience with past magnetometer missions has served as a useful guide to the Psyche MCRB in forming a priority list of hardware to test given their known magnetic properties or hypothesized magnetic characteristics. Several of these items have been tested early in the Psyche program and added as inputs to the Psyche DC magnetic model. For unit level tet data not yet available, placeholder magnetic dipole moments are input to the model either from hypothesized magnetic moment values or from actual data from similar units used in previous projects. Estimates can also be based on knowledge of magnetic material content, unit properties such as permanent or time-varying magnetic field emissions, susceptibility to magnetization (i.e. mass magnetization of saturated invar), its current loop area (based on actual circuit configuration or equivalent circuit model), and the DC magnetic allocations based on unit type.

Several of the high-impact DC magnetic assemblies have been characterized early in the project, namely units of the SEP chassis provided by Maxar. These include various latch valves, proportional flow control valves, cold-gas thrusters, and the SPT-140 Hall-effect thruster (shown in Figure 7). These units contain permanent magnets or high-current magnetic coils that are switched on and off often during flight. There are many cold-gas thrusters spread throughout the spacecraft in all directions for attitude control. Some valves and the Hall thrusters are deployed on two arms on opposing sides of the spacecraft. When possible, mitigation steps are taken to reduce magnetic impact from these units. An example consisted of mounting the deployed Hall thrusters and the propellant management assembly (that houses the latch valves) far away from the magnetometer sensors. Additionally, any pairs of the latch valves are mounted back-to-back for self-compensation of their magnetic moments in two axes. For Hall thrusters, although powered on magnetics test data show extremely large magnetic fields, it is only their remanent field that matters to the magnetics program since Hall thrusters will be unpowered during magnetometer science operations.

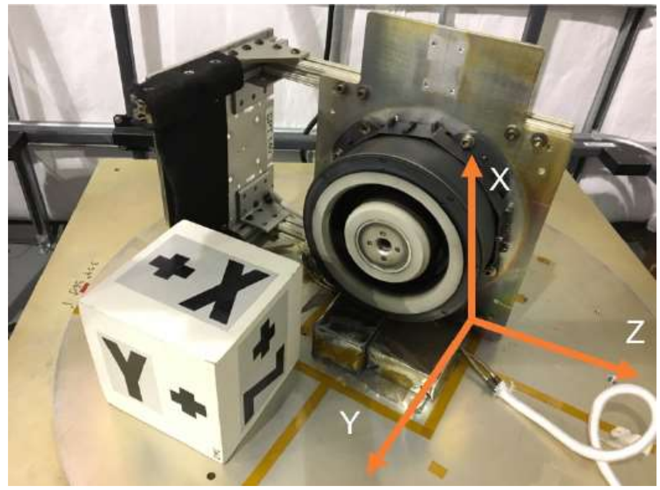

Figure 7. SPT-140 during magnetics testing

There are several other assemblies whose DC magnetic moments are high but well understood and are being mitigated accordingly. Within the telecommunication subsystem, these include traveling-wave tube amplifiers, waveguide transfer switches, and isolators. All these units are mounted on a dedicated equipment panel with power and avionics subsystems units at the bottom of the spacecraft. Two magnets of equal magnitude but opposing magnetic moment to the traveling-wave tube amplifiers will be mounted near them for compensation. The power distribution and spacecraft avionics assemblies that are also on this panel will be tested in the near future and compensation or other mitigation strategies will be employed if necessary.

Another high-impact assembly to DC magnetics is the DSOC payload. The DSOC team is working closely with the Psyche MCRB to ensure compatibility with the magnetometer science investigation. Due to DSOC's thermal stability needs, low coefficient of thermal expansion materials such as invar are used in the instrument's design. Invar is magnetically soft, which raises concern of magnetization during spacecraft integration and test as well as in flight. Invar samples from past projects and from the DSOC team were provided to the MCRB for characterization and incorporation into the DC magnetics model. Mitigation measures include heat treatment of the machined invar hardware and magnetic control of tools during fabrication and assembly. Other sub-assemblies of interest that are part of the DSOC payload are four struts that magnetically levitate DSOC from the Psyche spacecraft for isolation and stability. Each strut houses two permanent magnets and an electro-magnet. Although DSOC will not be powered during magnetometer operations, the eight permanent magnets will still affect the magnetometer data. The effect of the struts was minimized by placing them in a self-compensating configuration.

As discussed above, several mitigation approaches are available for highly DC magnetic hardware:

- Self-compensation is an option when two or more units of identical hardware are mounted back-to-back or in a way that the largest axial components of their magnetic moments oppose each other.

- Installation of compensation magnets is another approach available when a unit cannot be self-compensated.

- Demagnetization of hardware is also an option. Demagnetizing coils will be provided to Maxar by JPL with JPL-provided instruction and training. Most of the SEP chassis hardware will be installed on the spacecraft panels before final integration and test at JPL.

- Magnetic shielding is also available given mass and nickel content constraints. GRNS is highly sensitive to nickel and so the Psyche project tightly manages the nickel content on the spacecraft. Due to the high nickel content of traditional permalloy metal shields this mitigation method would be used as a last resort. Alternative high permeability, low-nickel content shielding materials are also being explored.

The tests, analyses, and mitigations above will ensure that the magnetometer instrument can successfully reject spacecraft-generated fields in flight. Two different methods will be used in flight to remove the spacecraft DC magnetic field. The first method, which can be employed when the spacecraft is in the solar wind, relies on the fact that on timescales of <~ 8 hours, the variability of the interplanetary magnetic field mainly involves rotation without changes in magnitude [4]. Because the spacecraft DC field is unchanging, the magnitude of the combined solar wind and spacecraft field changes as the interplanetary magnetic field rotates. This method has been used successfully in previous missions [5]. During intervals where the solar wind is not available (e.g., if the Psyche spacecraft were in a magnetosphere around the asteroid), magnetic gradiometry will be used to remove spacecraft DC fields [6]. This method makes use of the fact that the ambient field at the two sensors is the same while the spacecraft field is weaker at the outboard sensor.

Very Low Frequency Magnetics Methods

The frequency range 10^{-5} Hz to 0.1 Hz is of particular importance because expected variations in the asteroid remanent field as observed by the orbiting spacecraft fall within this range. Furthermore, spacecraft fields in this range are difficult to remove using gradiometry because the large size of the solar arrays means that their magnetic fields are similar at the two sensors. Yet another complication is that the solar array fields are expected to change as a function of their orientation, the distance from the Sun, and the power needs from the spacecraft.

The Psyche solar array features two five-panel wings, assembled as a cruciform. Each wing carries twenty-five 29.5% efficient ZTJ gallium arsenide triple junction solar cells. 35 cells are combined in series strings to provide the required voltage and thirteen strings are combined in parallel to form a stand-alone circuit. The photovoltaic assembly is a current source with an intrinsic voltage closely related to the array temperature – which over the course of the mission varies from +85 °C at Earth to -105 °C out at (16) Psyche. As a result, the solar array voltage increases by ~40% over the course of the mission and the array is sized to deliver 100 V at the target for maximum system efficiency.

The solar array is controlled by the power control unit to provide the spacecraft required power at an operational bus voltage of 100 V. In addition, the solar insolation difference between 1AU and 3.33 AU dictates that the power produced by the solar array ranges from 21 kW to 2.3 kW. To manage the voltage and the power ranges, the power control unit is designed to operate as a boost converter from 1AU to Psyche arrival and in the shunt mode after the encounter.

In both modes, the solar array current is routed through the solar array drive assembly through the power control unit and out to the flight system loads. In the boost mode, the solar array current supplied matches the spacecraft requirement by being stepped down by the amount determined by the ratio of the array operating voltage to the 100 V reference. In the shunt mode, the array current supplies the spacecraft loads directly and the excess power is short circuited inside the power control unit to be returned back to the array. This architecture allows for minimal changes in the solar array current as a function of time when measured over time period of weeks (and in the absence of the electric propulsion operating), therefore minimizing the impact to the magnetometer investigation:

- In the boost mode, the array current is stable to within the spacecraft load variations (nominally less than 5-7%)

- In the shunt mode, the array current is stable to within 100 mA over the entire array

The Psyche spacecraft's solar array magnetic analysis accounts for current flow from the arrays to the power control unit. Modeling the current flow given the layout design of the panel is key to understanding the consequential magnetic fields generated by the arrays and harnessing. Modeling the current loops within the solar array layout is the first step in the analysis. The solar array panels are designed by SolAero under a contract with Maxar. SolAero has delivered solar arrays for several NASA missions, including magnetometer missions like MAVEN and InSight. At the time of this paper, one panel layout had been modeled for magnetic loops. Granting a favorable analysis, the other panels would be designed within the same philosophy. Preliminary results of the panel's string layouts yielded minimal magnetic impact to the magnetometer. Although loops are present on the strings, the magnetic moments between neighboring strings are opposing and nearly equal in magnitude, thus becoming collectively self-compensating.

Future work for the solar array analysis includes modeling of the current accumulation on the panels through their diode trays into the interconnecting harnessing between panels and into the spacecraft. These currents are not negligible like individual strings or circuits. The interconnecting harnesses and support hardware are designed and provided by Maxar, creating a combined solar array assembly. Since the arrays are stowed for launch and deployed in flight, the harnesses used are lightweight sets of ribbon cable. While the spacing between wires in these harnesses provide the needed flexibility for deployment and mitigation for micro-meteoroids and orbital debris, it now presents a concern regarding current loop area. While the resulting magnetic moments may pose a non-negligible impact on the magnetometer, it must be noted that most of fields will not be in the 10^{-5}-0.1 Hz range but they will be DC (since some of these loops will not rotate with the array), which have been given a conservative allocation in the DC magnetics model. This analysis is still in work.

The Psyche project is also planning to test the solar array for magnetics as to validate the model described above. Specifically, DC magnetic measurements will be taken during a small-scale illumination test of the array. The size of the array precludes the use of a Helmholtz coil and so the Earth's magnetic field will be removed by using measurements of the ambient field taken with a handheld magnetometer. Then a portion of the solar array will be illuminated with a light source and the magnetic field will be measured again. The ambient magnetic field will be subtracted from the illuminated measurement to determine the magnetic field from the array. Results from this test will be extrapolated to the full array and will be used to validate the model above.

The test and analysis above will ensure that the magnetometer instrument can successfully reject solar array-generated fields in flight. In flight, we will calibrate for the solar array field by holding the solar array in a fixed position (facing the sun) and rotating the spacecraft 360° in two separate 180° steps. During this rotation, the spacecraft field, with the exception of the solar array, will remain constant in the sensor frame while the ambient field and the solar array field will rotate. If the ambient field in the solar ecliptic frame is constant during the rotation, we can use these measurements along with solar wind monitoring to separate the solar array field from the ambient field and spacecraft DC field. The results from the rotations will be compiled into a look-up table of solar array field values at each sensor for solar array angles at 5° increments.

AC Magnetics Methods

The Psyche AC magnetic test methodology is a departure from military and aerospace electromagnetic compatibility standard MIL-STD-461's AC magnetic radiated emissions RE01/RE101 testing. The standardized approach detected the AC magnetic fields with a loop antenna that is 5 or 7 cm away from the equipment under test depending on the loop antenna equipment used. The applicable frequency range in the standard is from 30 Hz to 100 kHz, which covers only part of Psyche's four requirement bands (discussed in Section 2), with gaps from 0.1 Hz to 30 Hz.

To accommodate the wider frequency range, Psyche AC magnetic testing leverages the capabilities of two sets of instrumentation: search coil sensors and dynamic signal analyzers. Both are sensitive to the entire Psyche frequency range. The former are custom-built devices built for JPL by UCLA and CNES, both calibrated to sense fields from 1 meter away from the unit under test. The sensors' raw data is fed into their respective preamplifiers. The preamplified data is then fed into the dynamic analyzer, which routes the data to the control computer. The raw data received by the dynamic analyzer is adjusted with the known correction factors of the search coil and cable loss, producing an adjusted, measured AC magnetic field expressed in dBpT (X dB above 1 picotesla). Measurements are made at three axes by rotating the unit under test and in operational modes applicable to Psyche. Testing is often performed on engineering or qualification models and not on flight hardware. Similarly to the DC measurements, the overall test setup varies in complexity depending on the power configuration of the assembly and the required ground support equipment. It is therefore critical to understand the operational models of each assembly that are relevant to the magnetometer investigation.

Measurements of the spacecraft assembly's AC fields using the method described above are input to an AC magnetics model that will be used to verify the magnetic cleanliness requirements. The model was developed at JPL to calculate the AC magnetic field at the inboard magnetometer due to the contribution from all assemblies on the spacecraft. Additionally, the model also calculates the decay factor between the two sensors. Inputs to the model are the measured AC magnetic field vectors from each unit after background subtraction, the location and orientation of those units on the spacecraft, and the locations of both the inboard and outboard magnetometer sensors. If a unit has been tested in various operational modes, those modes are linked to corresponding spacecraft operational phases (e.g., launch or science operations) in the model. Consequently, the spacecraft's AC magnetic field can be calculated for all phases of the mission by using the appropriate test data from each unit.

The residual sum of squares (RSS) is calculated from the AC magnetic field vector for each unit at each frequency. Since the orientation of each unit's AC magnetic field is dependent on the orientations of its internal electronic components, but that level of detail is finer than the scope of the AC magnetics testing plan, a conservative assumption is made: the RSS for each unit is taken to represent all three components of the magnetic field vector produced by that unit. The x-components of the AC magnetic fields sensed by the inboard and outboard magnetometer sensors are then calculated using the following formula:

$$B_{x,mag} = B_{RSS,unit}\left(\frac{1}{r_{mag}}\right)^3 \text{ [nT]}$$

The y- and z- axes follow the same format. At each magnetometer sensor, the AC magnetic field vectors from all units are summed over each frequency range to determine the AC magnetic field vectors in those ranges.

The decay factor for each frequency range is calculated as the ratio of the magnitudes of the AC magnetic fields at the inboard and outboard magnetometers in each range.

AC magnetic sources are abundant on a spacecraft, and the Psyche spacecraft is no exception. Any time-varying or frequency dependent operation such as clocks, motor stepping, command and data signals, can be a source of AC fields. The fields do not come exclusively from assemblies with large current changes (dI/dt) but also changes in voltage (dV/dt). For a given load, a dV/dt would result in a dI/dt and thus a time-varying magnetic field. Obvious sources of AC magnetic field emissions are the motors on the spacecraft. So far, preliminary testing has been performed on the Psyche imager motor that drives the imager's filter wheel and the solar array drive assembly motor that actuates the solar arrays. The two imager motors are at an intermediate distance from the magnetometer sensors and the two solar array drive assembly motors are at either side of the spacecraft. Thus, one solar array drive assembly motor is on the +Y side of the spacecraft, or within the same XZ plane as the magnetometer. While compensation may be a mitigation approach for DC fields, the primary mitigation mechanism for AC fields is shielding. As mentioned previously, magnetic shielding for Psyche is a balance between meeting magnetometer's magnetic cleanliness requirements and GRNS's nickel cleanliness requirements. High permeability, low-nickel or non-nickel shielding materials need to be characterized for shielding effectiveness (SEdB) from DC to 100 kHz.

Some less understood AC magnetic sources are the four reaction wheel assemblies on Psyche. These units are magnetically soft and their rotation presents an additional concern in the AC domain. Characterizing the reaction wheel assemblies on the ground requires extensive planning to define a suitable and relevant test configuration that is flight-like, since in reality the frequency of rotation will vary in response to the spacecraft's attitude and motion. The combined behavior of the four wheels together also needs to be assessed. Alternatively, the model may take a conservative approach by including all four wheels rotating at the same frequency. One of the early and preventive mitigations implemented by the project was to locate the wheels as far away from the magnetometer as possible (they are located at the bottom of the spacecraft). Similar to the case for the motors, magnetic shielding may also be an option if unit placement does not eliminate the concern.

In flight, AC field calibration will be conducted as a passive activity during initial check-out of the spacecraft. The magnetometer sensors will be turned on first in order to observe the magnetic signatures from the other instruments and components as they carry out their own calibration activities. Each time a signature with a magnitude above 0.65 nT at the inboard sensor is observed, how the observed field changed and which component was responsible for this change will be recorded. At the end of initial check-out, this information will be compiled into a table that lists the components with fields large enough for the magnetometer sensors to observe along with information on their dominant frequencies and their gradients at the positions of the two sensors. During science operations, ancillary data denoting the state of spacecraft components and pattern recognition software will be used to identify when a spacecraft AC field is observed. The housekeeping tables developed during initial check-out will be input into the spacecraft field removal software.

6. Considerations for System Integration and Test

The systems integration and test teams are responsible for assembling the final flight system including spacecraft and payloads. The bulk of the spacecraft is assembled in two phases, SEP chassis assembly, integration and test at Maxar and assembly, test and launch Operations (ATLO) at JPL. From the start of assembly, integration, and test through the completion of ATLO the teams operate with a similar set of objectives and procedures to preserve the magnetic cleanliness of the integrated spacecraft at launch. There are three key pieces to the magnetics cleanliness program for Psyche, 1) Team training / magnetics knowledge, 2) controlling the working environment around the flight vehicle, and 3) verifying to the extent possible the as built spacecraft.

Team training is crucial to preserving a magnetically clean vehicle. The Psyche program will establish a training program that provides a basic understanding of magnetics, an overview of common practices in I&T which should be monitored for a magnetically clean spacecraft, and awareness of how each person working on the spacecraft plays a role in preserving the best possible science return for the mission. As an example, a common practice during integration and test is installing and torqueing fasteners. The training program will help provide a reminder that some tooling may have a magnetic field associated with it, i.e. magnet driver bits. It will not be appropriate to use such tooling around sensitive components of the flight vehicle.

With the new understanding of magnetics, the team will be responsible for maintaining a magnetically clean zone around the spacecraft. The intent of the clean zone is to verify that all items entering the zone fall within the requirements for preserving a magnetically clean state of the spacecraft. A key aspect of the magnetics clean zone will be the screening station. All items (excluding those on an exempt list) will be screened by a hand held magnetometer. Should an item, such as a tool, be determined as magnetically "hot" it will be subject to degaussing prior to entering the clean zone. In a case where an item cannot be adequately degaussed the expertise of the magnetics engineer will be consulted prior to allowing or rejecting use with the spacecraft. Ones step beyond the magnetic clean zone there exists a sub zone around the flight Magnetometers, only titanium tools (or those approved by the magnetometer team) will be allowed to be used in the vicinity of the magnetometers once they are integrated.

Once the spacecraft reaches a state that is reasonably close to the final launch configuration (without solar arrays) the ATLO team will undertake a series of tests designed to characterize the magnetic signature of the spacecraft. In order to verify the DC magnetics, the ATLO team will perform a test where the unpowered spacecraft is displaced (a "swing" test) across multiple ground support equipment magnetometers to verify the DC signature of the spacecraft (see Section 7 for a discussion of other system-level test options currently under investigation). The test will be repeated along multiple axis of the spacecraft if deemed necessary. The ATLO team will take advantage of self-compatibility test to measure to the extent possible the AC signature of the spacecraft. Ground support equipment magnetometers which will be placed in close proximity to the spacecraft during test the test. The ultimate goal of the test is to power on all spacecraft subsystems in their operating modes. Even with the spacecraft almost full integrated, there will be an inability to test items such as the solar arrays due to limitation of being in a earth ambient environment. The power on cycle of each component should be seen by the ground support equipment magnetometers providing data to help correlate to the system model.

Once fully assembled and tested the ATLO team will maintain the magnetics clean zone around the spacecraft all the way through encapsulation with the launch vehicle and launch itself. The team will provide the same training to Launch Vehicle team members which need to work around the Psyche spacecraft. It is essential that the team maintain strict operating procedures at this point as there is limited time to correct any potential errors and the team must ensure Psyche is ready for launch.

7. Discussion and Summary

The Psyche magnetics control program is an effort to ensure that magnetometer science objectives are met within project cost and schedule constraints. This paper provides a snapshot of the program in the middle of Psyche's final design and fabrication phase (Phase C). Specifically, the paper focuses on the structure and approach to the program, while details on outcomes will be addressed in a future publication as the mission completes assembly, test, and launch operations.

The paper presents the constraints on allowable spacecraft-generated magnetic fields in various frequency ranges (from static to 100 kHz) as driven by the magnetometer science investigation. Corresponding requirements are verified using a set of models that take inputs from assembly-level magnetics testing. These requirements are in line with those from other missions like Juno and MAVEN. Table 1 shows a comparison of magnetic cleanliness requirements for these missions. While Psyche's requirements may seem more relaxed than those of other missions, these are expressed in terms of nano-Tesla and are therefore dependent on the distance between the magnetometer sensors and the spacecraft assemblies. Juno and MAVEN magnetometers where placed at the tip of their solar panels; Psyche's boom, however, is relatively short (2.15 meters), and so compliance to these requirements is not trivial therefore reinforcing the need for a rigorous magnetics program.

In the DC domain, test and modeling efforts are mature and already providing reliable estimates that can be compared with the requirement. AC magnetic field testing is more complicated and the assessment process is not as far along as the DC assessments. Specifically, most high-impact DC components have been tested for magnetics including Hall thrusters, cold gas thrusters, DSOC struts and invar samples, imager invar samples, latch valves, and traveling-wave tube amplifiers. Tests on the AC domain have only recently started, with data so far limited to the solar array drive assembly motor and the imager motor (two of the largest contributors in the AC domain). The DC magnetic model has extensive heritage and has been used in many previous missions. The AC model has been first developed specifically for Psyche to include a larger frequency range as well as spacecraft operational modes and it is still under review by subject matter experts. As of the drafting of this paper, initial estimates from both the DC and AC models suggest that the magnetic cleanliness requirements can be met.

The approach to system level testing is also under discussion. Specifically, a static test where the spacecraft does not have to be displaced is under evaluation. This test approach consists of placing a set of ground support equipment magnetometer trees surrounding the spacecraft to take multi-point measurements of its magnetic field. Background measurements need to be performed with the same magnetometer configuration but prior to rolling in the spacecraft. This test approach may provide better measurement performance than a "swing" test and may allow us to obtain magnetics data in a powered on configuration.

Table 1. Requirement comparison with other missions

Mission	DC Requirement	AC Requirement
Psyche	30 nT at inboard MAG sensor	1 nT (0.1-16 Hz) at inboard MAG sensor
Juno [7]	2 nT at MAG sensor	0.5 nT (time-variable) at MAG sensor
Maven [8]	2 nT at MAG sensor	0.25 nT (time-variable) at MAG sensor

Psyche presents several unique challenges when compared to other missions. The nature of the relationship with Maxar, the spacecraft vendor, relies on high-heritage assemblies and the acceptance of Maxar existing processes. Therefore, re-design of hardware components is typically not in scope and resolution of exceedances are limited to mitigation approaches including assembly placement, shielding, or compensation. The magnetics program also faces technical challenges in relation to the approach to verification of the

AC magnetic cleanliness requirements. Specifically, minimization of the ambient noise during AC magnetics testing for frequencies below 100 Hz is key to providing meaningful inputs to the AC magnetics model. Given the stringent requirements in this frequency range, background removal techniques are also under development to minimize the effect of the data contamination due to existing facility-generated magnetic fields.

APPENDIX

A. DETAILED SCIENCE DERIVATION OF REQUIREMENTS

As stated in Section 4, the magnetic cleanliness requirements are driven by the need to detect Psyche's internal field and distinguish it from external fields (due to the solar wind and the spacecraft). If (16) Psyche is a core, it is may have a strong remanent magnetic field. In particular, the magnetometer experiment is designed to be able to detect a minimum dipole moment of 2×10^{14} A-m^2 by the end of the mission. To demonstrate that this can be done within the uncertainty budget of +/-1.5 nT or 3% of the measured field (whichever is larger) 3σ per axis, we simulated the interaction of a magnetized Psyche with the solar wind field expected in the asteroid belt using a hybrid plasma model [3]. We extracted magnetic field data from the simulations using the lowest orbit planned for the mission, and added random noise to each measurement point, from a Gaussian distribution with a 2.5 nT 3σ width. Data were then binned into spatial locations around the body, and the mean of each of the magnetic field components were calculated. This gives the signature of the internal field. To verify the requirements could be met, we considered the worst-case scenario, by 1) simulating a case where Psyche possesses the lowest possible magnetic moment of $2\text{x}10^{14}$ A-m^2, and 2) taking only 5% of the data gathered in each spatial bin, to account for solar wind variations that may make some data invalid. We demonstrated that under these conditions, certain locations around the body give rise to a signature of an internal field of 8 nT that can be detected over a background of 2 nT background solar wind field.

In order to meet the uncertainty requirement, it is necessary to remove the spacecraft generated magnetic fields from the observations. The main tool that we have to accomplish this is magnetic gradiometry. This technique uses two sensors on a boom at different distances from the spacecraft bus and relies on the fact that magnetic fields fall off as the distance from the source increases. The equations used to estimate the spacecraft field at each sensor were developed by [6],

$$\vec{B}_{in}^{est} = (1-\alpha_{ii})^{-1}[\vec{B}_{in} - \vec{B}_{out}]$$

$$\vec{B}_{out}^{est} = \alpha_{ii}(1-\alpha_{ii})^{-1}[\vec{B}_{in} - \vec{B}_{out}]$$

where $\vec{B}_{in}$ and $\vec{B}_{out}$ are the measurements at the inboard and outboard sensors respectively. The term in brackets on the right-hand side ($\vec{B}_{in} - \vec{B}_{out}$) is referred to as the differenced field ($\vec{B}_{diff}$). The α terms, or coupling coefficients, are the entries in a diagonal matrix that describe the decay for each of the components of the magnetic field between the two sensors. For a dipole source that lies along the magnetometer boom axis, the entries are identically $(r_{in}/r_{out})^3$. When the source is off-axis the entries depend on both the direction of the source magnetic moment and the distance to the sensors. The uncertainty in this calculation is driven by two factors: 1) the uncertainty in the coupling coefficients, and 2) the ratio of $\vec{B}_{diff}$ to the instrument noise (n) where the error in the gradiometry calculation becomes larger as $\vec{B}_{diff}/n$ gets smaller. For strong fields (>>1 nT) uncertainty in the coupling coefficients is the dominant source of error. For weak fields (<1 nT) the dominant source of error is $\vec{B}_{diff}/n$. As a result, the limits on the coupling coefficients are different for weak and strong fields. For fields in between, the limits on the viable coupling coefficients depend on the specific source/sensor geometry (i.e. how far off-axis the source is and how well we know the direction of the sources magnetic moment).

In order to derive the requirements on the DC field a series of simulations were conducted for spacecraft magnetic fields that had magnitudes between 20 and 120 nT at the inboard sensor. For each simulation a model of the total measured field was composed that included, a spacecraft DC field made up of multiple dipole sources, an ambient field and instrument noise at each sensor. A best-fit dipole center (position and direction) was determined using a dipole approximation in order to calculate the coupling coefficients for each field configuration. The modeled spacecraft DC field was then added to a time series with a varying ambient field and instrument noise, and the gradiometry equations, with the estimated coupling coefficients, were used to calculate estimates of the spacecraft field at the inboard and outboard sensors for each timestep. The estimates were then compared to the values from the field model to determine the maximum error in the gradiometry calculation. Results from an ensemble of more than 4000 simulations, in conjunction with the uncertainty budget for the overall magnetic field reconstruction, were used to set the requirements on the DC field. All of the spacecraft field configurations with magnitudes <30 nT and coupling coefficients of <0.66 satisfied the requirement for the uncertainty in the DC field calculation when instrument noise is considered (<0.8 nT).

The main source of low frequency magnetic fields (10^{-5} to 0.1 Hz) is expected to be the solar array. The field generated by the solar array is essentially a DC field that is observed as a low frequency field due to the relative motion of the array with respect to the magnetometer sensors. The maximum field is based on our ability to separate the solar array field from the spacecraft DC field and the ambient field in-flight in conjunction with the expected variation in the solar array field during the mission. Using a single magnetic moment of 0.7 A-m^2 centered on each panel, the resulting magnetic field is 2.1 nT at the inboard sensor. The uncertainty in using a table of magnetic field values for each sensor, as a function of solar array angle, to remove this field is <0.85 nT given the expected variations in the solar array field. When taken together with the uncertainties in removing the spacecraft DC and AC fields, this allows us to stay within the uncertainty budget for the reconstructed magnetic field. A coupling coefficient of 0.75 (field decay factor of 1.3) guarantees that we will be able to use gradiometry to validate/update the tables in-flight using $\vec{B}_{diff}$.

The derivation of the AC (0.1-16 Hz) requirements was also based on a combination of single fault tolerance and gradiometry. The ability to meet low level science requirements with only the inboard sensor was the driving factor since, without a second sensor, we have no way of rejecting the AC field. The maximum field of 1 nT/axis at the inboard sensor allows us to meet level 1 requirements in the event that the outboard sensor fails. The minimum value for the field decay factor guarantees that we will be able to use gradiometry to effectively remove the AC field using both sensors. Since the AC fields are much smaller than the DC fields a larger coupling coefficient is required to make sure the difference in the measurements at the inboard and outboard sensors is large enough to allow for gradiometry. In general, the differenced field needs to be twice as large as the instrument noise in order for flight system fields to be reliably detectable by both the inboard and outboard sensors.

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BIOGRAPHY

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 worked on the definition of space radiation environments and supported radiation analyses and testing for multiple instruments and spacecraft components. In 2017, she joined the Psyche project as the instrument engineer for Psyche magnetometer. Her areas of expertise include space environments, particles and fields instrumentation, and space systems.*

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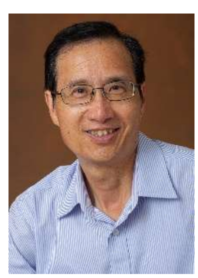

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Peter W. Lord *received a B.S in Mechanical Engineering from Syracuse University in 1984 and a M.A in Liberal Arts from Stanford University in 2002. He holds multiple patents for spacecraft antenna technology. His experience includes the development of entirely new types of commercial space applications, most notably as Lead System Mechanical Engineer for the inaugural Sirius Satellite Radio Constellation. Mr. Lord served as both Systems Lead and Proposal Manager for Maxar's NASA study "Adapting Commercial Spacecraft for the Asteroid Redirect Mission" and as Phase A Program Manager for the Psyche SEP chassis. He is currently the Technical Director and Deputy Program Manager for the Psyche SEP Chassis.*

Catherine Keys *holds a B.S.E. in Earth Systems Science and Engineering and a M.E in Engineering from the University of Michigan. She has over 8 years of experience at SSL as a space environments engineer. Her responsibilities include radiation testing of piece parts, unit and spacecraft evaluation for total dose, EMC, venting, and overseeing the space environment design of various spacecraft programs.*

Lindy Elkins-Tanton *is the Principal Investigator of the NASA Psyche mission, Managing Director of the Interplanetary Initiative at Arizona State University, and co-founder of Beagle Learning, a tech company training and measuring collaborative problem-solving and critical thinking. Her research and efforts are focused on a positive human space exploration future, the effective leadership of teams, and education for the future of society. In 2010 she was awarded the Explorers Club Lowell Thomas prize. Asteroid (8252) Elkins-Tanton is named for her. In 2013 she was named the Astor Fellow at Oxford University. She is a fellow of the American Geophysical Union, and of the American Mineralogical Society, and in 2018 she was elected to the American Academy of Arts & Sciences. Elkins-Tanton received her B.S., M.S., and Ph.D. from MIT.*

Jodie Barker Ream *received a Ph.D. in Space Physics from UCLA in 2015. She taught undergraduate courses in Physics and Astronomy at Utah Valley University from 2015 to 2017. In 2018, she joined the Psyche Magnetometer group at MIT as a Research Scientist. Since then she has been working to develop methods for calibrating magnetic field measurements collected in space with a focus on removing the magnetic field signatures generated by the spacecraft from the observations.*

Benjamin Weiss *is Professor of Planetary Sciences at the Massachusetts Institute of Technology. He studies the formation, evolution, and history of planetary bodies, with a focus on paleomagnetism and geomagnetism, geophysics, meteoritics, and habitability. He emplous laboratory analyses of geological samples, in situ spacecraft observations, and fieldwork around the Earth to understand the history of planetary geological and geochemical processes. He is the Magnetometry Investigation Lead on the Psyche mission.*

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Shirley Hart is the lead Environmental Requirements Engineer for Psyche project at NASA's Jet Propulsion Laboratory. She is also the lead Environmental Requirements Engineer for Deep Space Optical Communications (DSOC) project, a technology demonstration payload hosted by the Psyche mission. From 2015 to 2017, she served as the Senior space radiation engineer at Linear Technology Corporation. From 2007 to 2015, she held the position as Senior space environments engineer for Space Systems Loral (SSL). Shirley holds two B.S. from University of Colorado at Boulder, in Electrical Engineering and Physics.