

Psyche Mission's End-to-End Information System Verification & Validation: Planning, Execution, and Lessons Learned

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Abstract

The Psyche mission is a National Aeronautics and Space Administration (NASA) discovery class mission managed by the Jet Propulsion Laboratory (JPL) that will explore a possibly metal world—an asteroid known as (16) Psyche located in the asteroid belt between Mars and Jupiter. The Psyche Mission launch period begins in October of 2023 after an intense and rigorous phase of system testing including verification and validation (V&V) of the End-to-End Information System (EEIS). The EEIS is a virtual system comprised of distributed functions across the flight system, launch vehicle, mission system and science system, that interoperate cooperatively to collect, transport, store, translate, integrate, and manage mission (e.g., science, engineering, radio metric, command, ancillary) information. Core elements of the Psyche EEIS include the space link, Deep Space Network (DSN), ground data system, flight system, instruments, and timekeeping functions. The EEIS engineering team is responsible for ensuring the architecture is accurately implemented and that the project has a comprehensive understanding of the system's functions and operability. This paper will explore the scope and results of EEIS testing, and will analyze the challenges faced and lessons learned from the V&V campaign. The completed V&V activities are defined as part of the EEIS phased development and test plan (PDTP) which outlines the scope of various system-level tests, associated requirements and stakeholders, necessary venue and support, and the timeline on which the tests will be accomplished. EEIS testing includes verification of: high-level data interfaces; requirements on the quality, quantity, completeness, and latency of the system's data; performance and functional requirements; end-to-end command, telemetry, and science data flow; some lower level mission and flight system requirements; and data accountability validation. While these tests are successfully executed through the implementation of institutional best practices, the project faced a number of technical and organizational challenges in executing robust system tests. This paper will explore some of the unique challenges in the verification and validation of the EEIS including programmatic challenges, cross-subsystem tests with multiple stakeholders, and the development of features in flight software and testing venues. This evaluation of the EEIS V&V planning, execution, and lessons learned effectively informs future space missions on best practices and recommended approaches in system level communication testing.

Keywords: Psyche, EEIS, Communications, Verification, Testing

Acronyms

AOS = Advanced Orbiting Systems
APL = Johns Hopkins University's Applied Physics Laboratory
ASU = Arizona State University
ATLO = Assembly, Test, and Launch Operations
AVS = Avionics
BPS = Bits per Second
CAV = Clock Adjust Values
CCSDS = Consultative Committee for Space Data Systems
CDR = Critical Design Review
CFDP = CCSDS File Delivery Protocol
CLTU = Command Link Transmission Unit
CM = Change Management
CMD = Command
CRC = Cyclic Redundancy Check
D/L = Downlink
DSN = Deep Space Network
DSOC = Deep Space Optical Communication
DTU = Denmark Technical University
ECR = Engineering Change Request
EEIS = End-to-End Information System
EHA = Engineering, Housekeeping, and Accountability
EM = Engineering Model
ERT = Earth Receive Time
EVR = Event Record
FEI = File Exchange Interfaces
FER = Frame Error Rate
FGICD = Flight Ground Interface Control Document
FP = Fault Protection
FS = Flight System
FSTB = Flight System Testbed
FSW = Flight Software
FSWTB = Flight Software Testbed
GDS = Ground Data System
GLR = Ground Laser Receiver
GLT = Ground Laser Transmitter
GRNS = Gamma-Ray and Neutron Spectrometer
GRS = Gamma-Ray Spectrometer
HGA = High Gain Antenna
HK = Housekeeping Data
HW = Hardware
I&T = Integration & Test
IP = Internet Protocol
IPSO = Integrated Psyche Systems Organization
IRB = Independent Review Board
JPL = Jet Propulsion Laboratory
LGA = Low Gain Antenna
LV = Launch Vehicle
MAG = Magnetometer
MDNav = Mission Design and Navigation
MIT = Massachusetts Institute of Technology
MOS = Mission Operations Systems
MPST = Mission Planning & Sequence Team
MS = Mission System
MST = Mission Scenario Tests
NASA = National Aeronautics and Space Administration

NS = Neutron Spectrometer
NVM = Non-Volatile Memory
ORT = Operational Readiness Tests
OWLT = One-Way Light Time
PCE = Psyche Compute Element
PDA = Power Distribution Assembly
PDR = Preliminary Design Review
PDS = Planetary Data System
PDTP = Phase Development and Test Plan
PI = Principal Investigator
PLA = Payload Launch Adapter
PLD = Payload
PSE = Project System Engineer
QQCL = Quantity, Quality, Continuity, and Latency
RF = Radio Frequency
S/C = Spacecraft
SCID = Spacecraft Identification
SCLK = Spacecraft Clock
SCT = Spacecraft Team
SDC = Science Data Center
SDST = Small Deep Space Transponder
SEM = Stationary Electronics Module
SEP = Solar Electric Propulsion
SIA = Serial Interface Adapter
SLE = Space Link Extension
SOST = Science Operations Support Team
SPK = Spice Kernel
SSE = Simulation and Support Equipment
SW = Software
TAYF = Test As You Fly
TC = Time Correlation
TCP = Transmission Control Protocol
TDB = Barycentric Dynamical time
TIF = Telecom Interface
TLM = Telemetry
TVAC = Thermal Vacuum
U/L = Uplink
UTC = Universal Time Constant
V&V = Verification & Validation
VA = Verification Activity
VAC = Verification Activity Collection
VC = Virtual Channel

1. Introduction

1.1 Psyche Project & Mission Objectives

The Psyche Mission is a journey to a metal world, a large asteroid known as (16) Psyche. One of the largest in the solar system, (16) Psyche is a potential M-type asteroid and remnant nickel-iron core of a once rocky body. The asteroid orbits the Sun between 2.5-3.3 au. After a launch date in October 2023 aboard a Falcon Heavy Launch Vehicle (LV), and a 6-year cruise with a Mars gravity assist, the flight system will explore the metal world. *Figure 1* depicts the mission timeline for this Discovery class mission. Over four Science Orbits, the Psyche mission will conduct observations using four instruments—a magnetometer (Mag), gamma-ray (GRS) and neutron (NS) spectrometers, redundant multispectral imagers, and gravity science (using a X-band high gain antenna and three low gain antennas) [1]. The mission also includes an optical communications technology demonstration (DSOC).

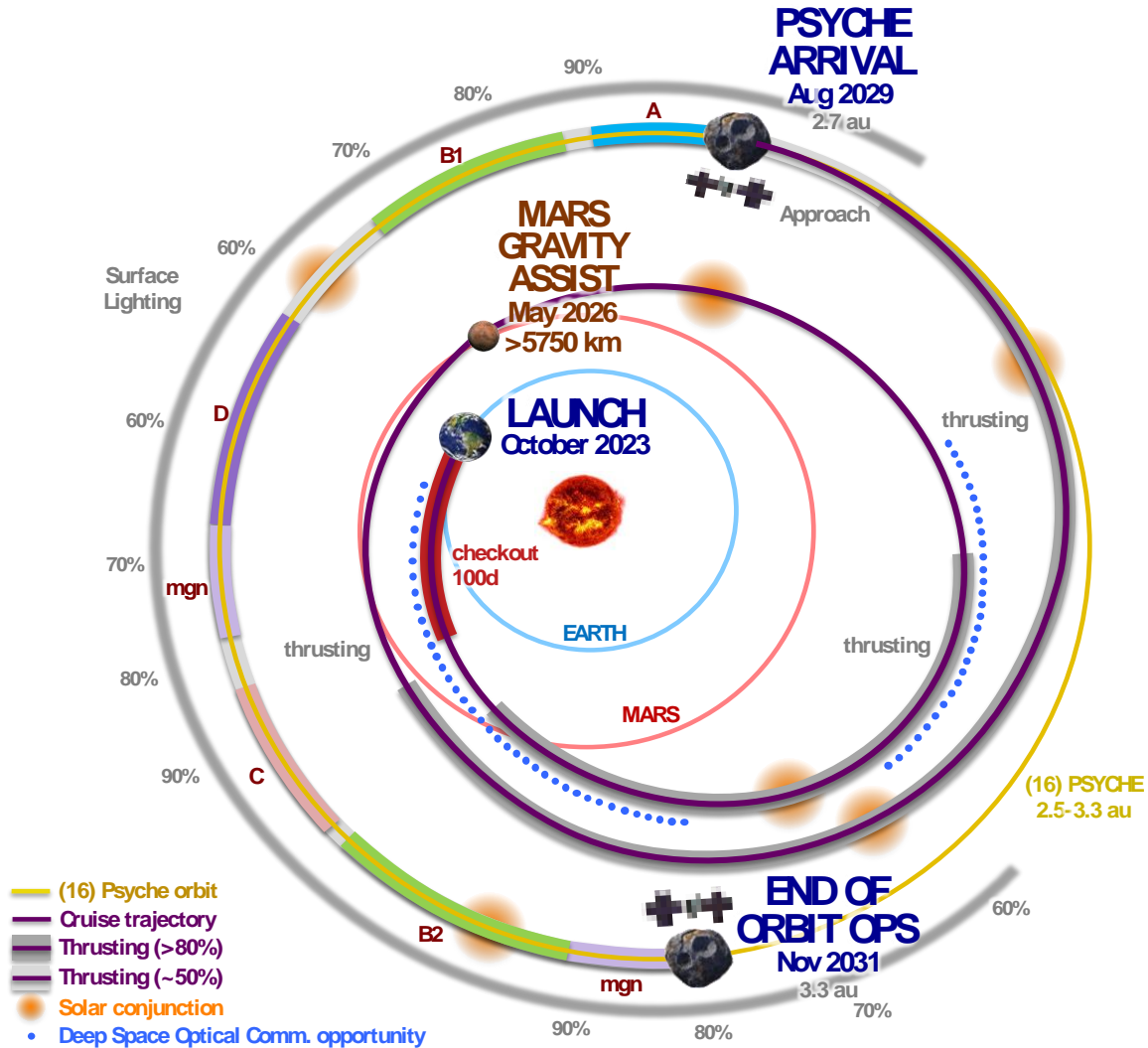


Fig. 1. Psyche Mission Overview

The Psyche project is organized into a Science System, Flight System (includes Spacecraft and Payload), a Mission System (including the Mission Operation System (MOS), Ground Data System (GDS), Mission Design and Navigation (MDNav), and the Science Data Center (SDC) at Arizona State University (ASU)). Overall, the project consists of multiple organizations including the following: JPL provides the project management, elements of the power, avionics, and telecommunication subsystems, integration and testing, and mission operations; ASU provides the Principal Investigator (PI, Dr. Lindy Elkins-Tanton) and Deputy PI (Dr. Jim Bell), the multispectral imager and the SDC; MAXAR provides the Solar Electric Propulsion (SEP) chassis; Johns Hopkins University’s Applied Physics

Laboratory (APL) provides the Gamma-Ray and Neutron Spectrometers (GRNS); Massachusetts Institute of Technology (MIT) provides gravity science and magnetometer science; Denmark Technical University (DTU) provides the magnetometer; Malin Space Systems is the Imager instrument vendor; NASA and SpaceX provide the Launch Services and the Falcon Heavy Launch Vehicle; and NASA-JPL provides the DSOC technology demonstration. DSOC is a demo and not part of the core mission objectives but will prove the use of optical communications from deep space spacecraft. The Psyche spacecraft also carries a 2.0m fixed Cassegrain high-gain antenna (HGA) and three low-gain antennas (LGA) for nearly full sky coverage.

If (16) Psyche is the exposed metal core of a once rocky body, whose exterior has been stripped away by collisions and impacts, then it presents a rare and unique instance of a planetary core that can be observed. The following are the Psyche Project’s five science objectives:

1. Determine whether Psyche is a core, or if it is primordial un-melted material.
2. Determine the relative ages of Psyche’s surface.
3. Determine whether small metal bodies incorporate the same light elements into the metal phase as are expected in the Earth’s high-pressure core.
4. Determine whether Psyche was formed under conditions more oxidizing or more reducing than Earth’s core.
5. Characterize Psyche’s topography.

1.2 Project System Engineering

The Project Systems Engineer (PSE) is responsible for project technical integrity including mission risk and performance to meet the driving scientific and technological objectives. The PSE is the engineering technical authority and is responsible for the planning and implementation of the system engineering function across the entire scope of the project. The PSE team is comprised of the PSE leadership, project V&V engineers, change management (CM) team, EEIS engineering team, and phase leads who oversee key time periods (i.e., launch, cruise, and orbital) in the mission’s operation. The engineering organization on the project changed over the course of the mission development lifecycle to meet the needs of the project.

The project initially followed a traditional engineering organization structure for a JPL flight project. This traditional structure included the project system, flight system (FS), mission system (MS), and payload (PLD) engineering teams spanning high levels of the system to subsystem level engineering. See *Figure 2* for a high-level view of Psyche’s initial organization.

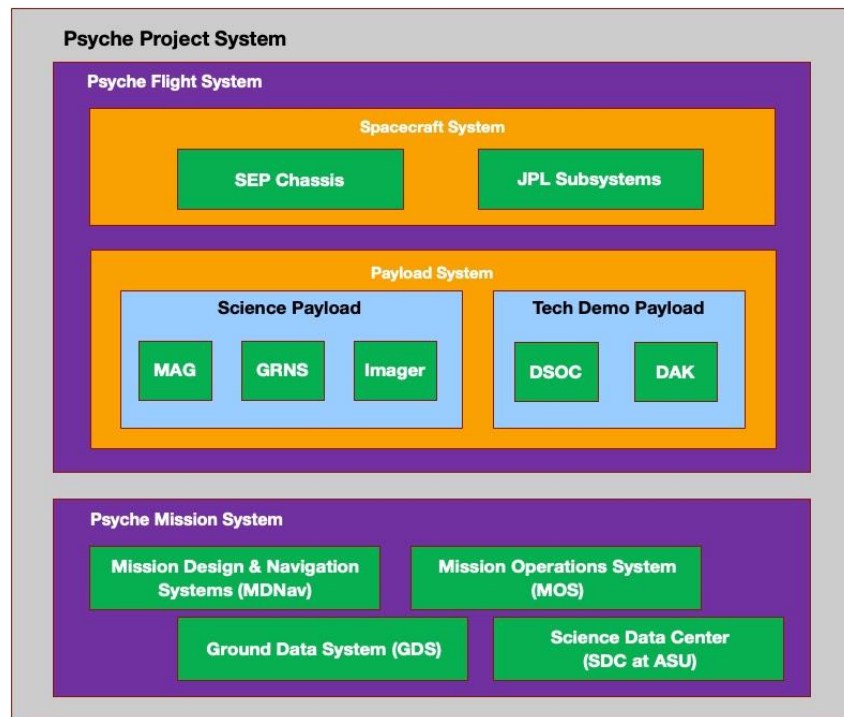


Fig. 2. System Engineering Team Structure

In the system level test phase, the domain lead role was introduced. Domain leads are subject matter experts on the project who oversee functional areas of the mission rather than specific subsystem areas. This leadership structure enables cross-system functions to have better stakeholder-ship and enables more flight-like testing focused on validating the system. Domain leads were responsible for the verification roll-up in their domains, communicating status updates to management, and reviewing the development and execution of related system tests and requirement closures. Domains on Psyche include payload, avionics (AVS) and the EEIS, fault protection (FP), guidance navigation and control (GNC), behaviors, and power [2].

Following the decision to delay the launch of Psyche from 2022 to 2023 in order to enable more comprehensive testing, the project’s engineering teams were reorganized to be more streamlined with direct communication. This restructuring resulted in what is known as the Integrated Psyche Systems Organization (IPSO)—a combined flight, mission, payload, and project system which includes an overall manager and key system leads, the flight software team, testbeds teams, domain leads, and phase leads. The structure includes an adjacent payload office, mission system office, and flight system management. This change was made to establish clear and complete ownership of phase and functional domains, better balance the scope of functional domains, improve project communication and teamwork, and help prioritize competing tasks on the project.

1.3 Project Verification & Validation

Verification asks whether we built the system right and validation asks whether we have built the right system. Verification, thus, confirms compliance with the requirements using test, analysis, inspection, demonstration methods. Then, validation confirms that verified end product fulfils its intended use when placed in its intended environment. Validation emphasizes end-to-end scenario testing, focuses on needed capabilities rather than requirements. The Psyche project V&V went through several organizational structures originally the project was structured around a traditional mapping of Verification Activity Collection (VAC) to Verification Activity (VA) to Requirement structure (Figure 3) [3].

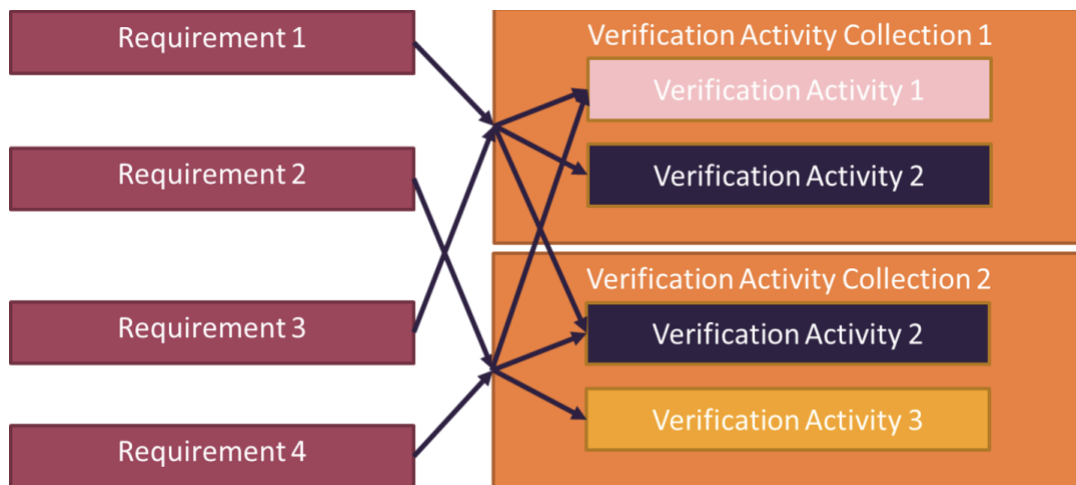


Fig. 3. Requirement Mapping to Verification Activity Assignments

The VACs were broken out into 4 larger areas: Project System VACs, Flight System VACs, Payload System VACs & Mission System VACs. Later in the project it was determined that the management of the Flight System VACs was becoming too cumbersome to manage without an additional layer of management and a Domain Lead Verification structure was established (Figure 4). Finally, after the project launch slip the V&V organizational structure was redesigned again to support an IPSO which was designed to help clarify the priorities across the project and ensure that a single team had responsibility for the V&V across the project. A lesson learned from these structural changes is that while these changes were likely necessary to ensure the Project V&V could be completed, each change in itself imposed a significant cost in both schedule and personnel resources for the project. To avoid this churn for future projects it is important for Project V&V engineers to identify which V&V organization is likely to work best for their mission & obtain buy in from the other systems engineering organizations across the project for that structure—especially if that structure is needed to change over time [4].

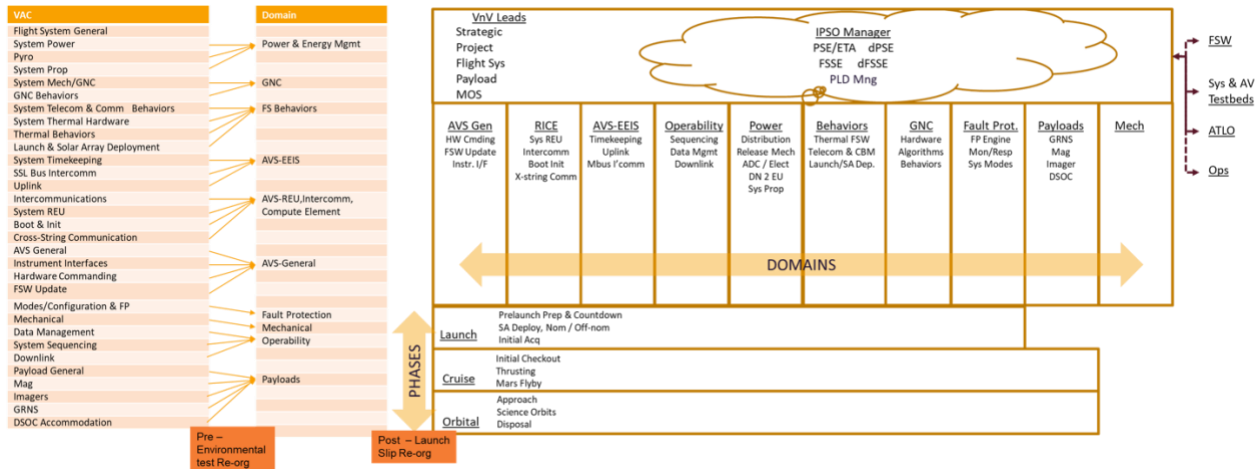


Fig. 4. Project V&V Reorganizations

1.4 End-to-End Information System

The EEIS is a virtual system that includes a set of functions and success criteria across the flight system, launch vehicle, mission system and science system, that interoperate cooperatively to collect, transport, store, translate, integrate, and manage mission information (e.g., science, engineering, radio metric, command, ancillary). These functions are performed cooperatively by flight and ground elements to achieve mission objectives. The EEIS is a cross-cutting function of Project System Engineering.

The EEIS engineers address operability considerations such as data visibility, controllability, and predictability and work interfaces among and between users, ground data systems, and space flight system. Information types communicated across the EEIS include telecommand data, collected science measurements, engineering housekeeping data, timekeeping information, and data accountability [1].

A high-level view of the subsystems and interfaces which comprise Psyche’s EEIS are illustrated in Figure 5 [5].

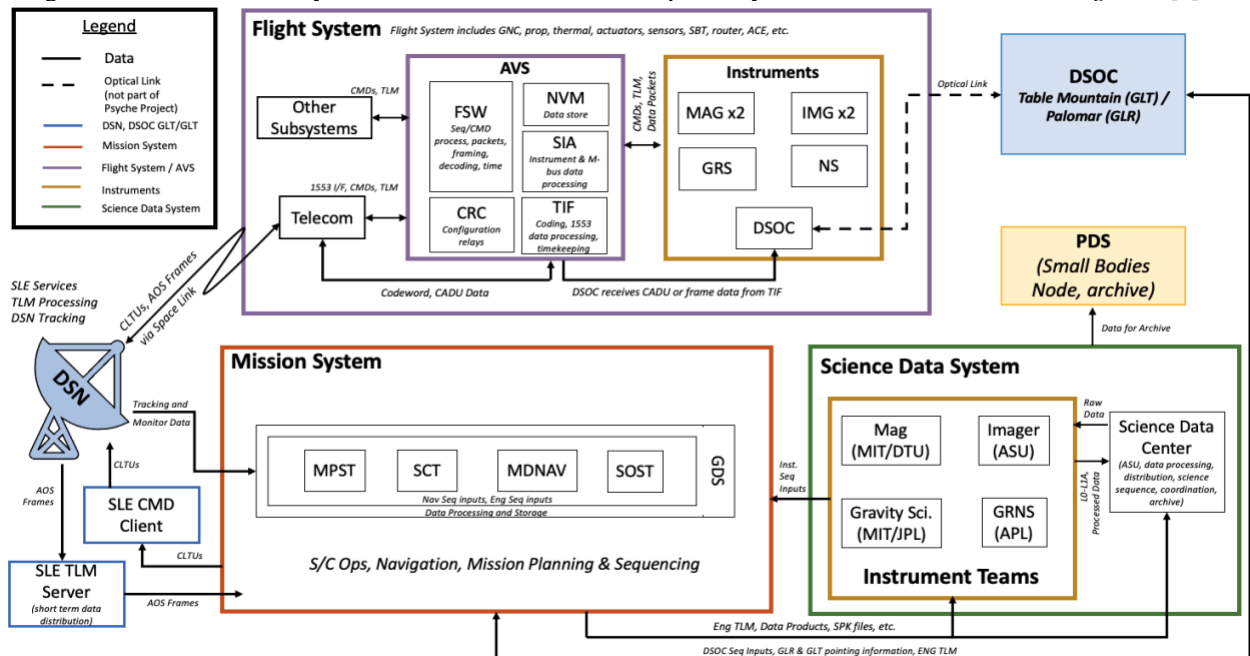


Fig. 5. High-Level EEIS Diagram

Data Quality, Quantity, Continuity, and Latency (QQCL) offers EEIS engineering with four prime metrics for both specifying requirements and evaluating the performance of the data accountability of the project’s EEIS.

- **Quality:** Metric speaks to how “good” or “bad” the telemetry (TLM) is in terms of errors introduced into the telemetry once it is generated by the source (instrument or engineering subsystem) on board the spacecraft (S/C). This metric is specified in terms of a transfer frame error rate (FER).
- **Quantity:** Metric speaks to the volume of data telemetered by the spacecraft to the destination(s).
- **Continuity:** Metric speaks to the tolerance of the EEIS to the size and frequency of losses i.e., data gaps in the telemetry. The EEIS engineer specifies data continuity requirements as part of the end-to-end accountability design.
- **Latency:** This speaks to the amount of time a user must wait before receipt of the data. Depending upon the needs of the MOS and PIs, the EEIS engineer specifies data latency requirements such that the expectations of the end users of the EEIS will be designed into the system and tested. Data latency requirements are needed to ensure that data will be received by the end users based upon negotiated pre-agreements.

A number of communications protocols, as shown in *Figure 6*, are selected and implemented to enable successful data links across the EEIS. These protocols are defined by a number of standards for payload and other flight system data formats data bus protocols, space link and CCSDS File Delivery Protocol (CFDP) protocols, ground network protocols, data monitoring, and space link extension (SLE) [2, 6-10].

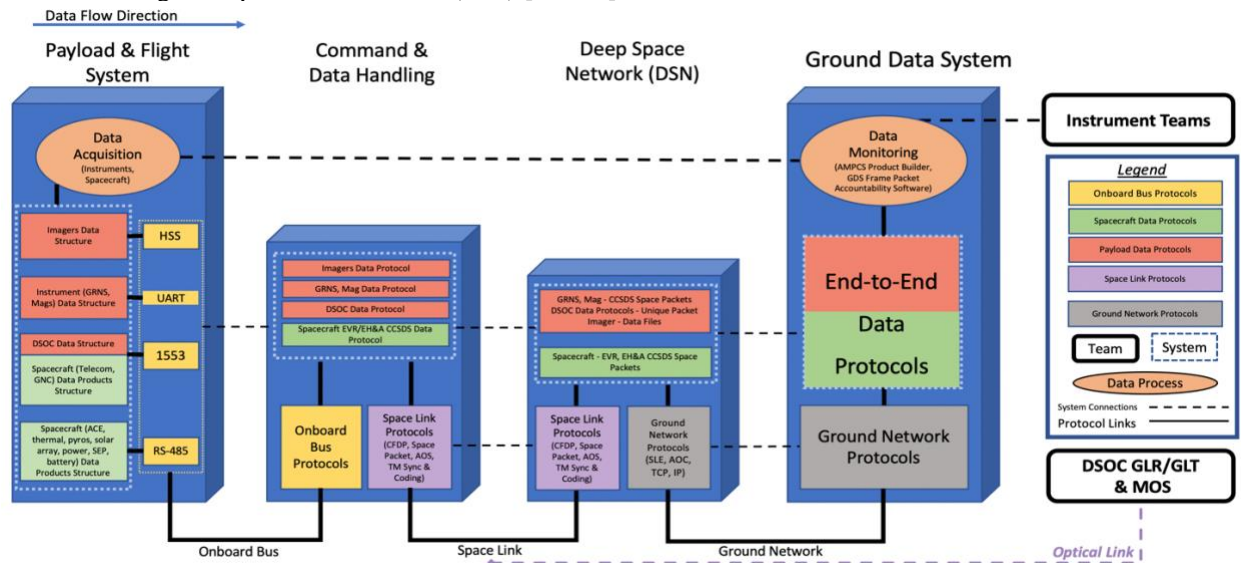


Fig. 6. High-Level Psyche EEIS Communications View (Downlink)

1.5 End-to-End Information System Engineering

The overarching purpose of the EEIS Engineer is to unify and advance the JPL Multi-mission flight/ground Software and EEIS architectures to enable future missions to succeed within the context of NASA’s plans and applicable global flight/ground interoperability.

The primary EEIS engineering deliverables include:

- developing high-level requirements for the end-to-end data flow’s performance and functional characteristics and ensuring those requirements are mapped to lower level requirements at the subsystem levels;
- analyze and determine the features, advantages, and constraints of the end-to-end design;
- conduct analysis and modeling for the data flow characteristics;
- write documentation on the concept architecture, test plans, time architecture, and flight-ground interface;
- and plan, execute, and document the testing and closure of requirements on the EEIS.

This role is unique to JPL and not typically practiced in this form at other NASA centers, in the private sector, or at other space agencies but is advantageous as it enables robust interface oversight and tightens both team and architecture coordination across the mission phases. The EEIS engineering team's primary responsibilities in each phase are as follows:

- Pre-Phase A (Advanced Studies) – Generate EEIS operations concepts
- Phase A (Mission & System Definition) – Provide EEIS architectural design
- Phase B (Preliminary Design) – Conduct flight/ground information system trades; generate EEIS level 2 requirements
- Phase C (Design & Build) – Develop the EEIS Phased Delivery and Test Plan and begin coordinating and conducting the tests
- Phase D (Assembly, Test and Launch Operations, ATLO) – Lead and coordinate EEIS testing

Key practices in implementing a successful EEIS architecture include:

- A concurrent engineering approach for the development of flight, ground, mission and science systems;
- Use of fundamental EEIS architectural concepts: push functions into the lowest layer possible, make lateral tradeoffs within a layer, and use heritage capabilities wherever possible, not just where it is convenient;
- An incremental development and test approach;
- An EEIS design emphasizing operability features in flight, ground, mission and science systems including integrated ground and flight-based tool sets.

The concurrent engineering approach is carried out by having coordinated project system engineering led by the Project System Engineering Team. Thus, the EEIS engineer is both a highly technical as well as a key coordination role between managers and the system engineers responsible for the mission design, S/C, GDS, MOS, and instruments.

2. V&V Planning

2.1 V&V Process & Venues

V&V Planning should be done continuously throughout a project's lifecycle, early in the project development the planning is focused on requirement validation and high-level grouping of Verification Activities and integration into the ATLO & testbed schedules. As the project approaches its critical design review, V&V planning moves more towards the details of what work should be done by each of the identified Verification Activities. Post critical design review (CDR), this work turns to a much more tactical schedule, rearranging the activities as they are executed and reviewed to best fit the project ATLO and testbed schedules.

2.2 Planning & Requirements

One important aspect to V&V planning is the development and validation of the project requirements, *Figure 7*. This includes understanding requirement verifiability, traceability, and structure. On Psyche, the decision was made to write a number of traditionally lower-level EEIS requirements at the project level (L2). This led to a situation where in order to preserve tractability those requirements were often duplicated at the system level (L3) and the subsystem level (L4) which resulted in duplicate and un-necessary verification work. While the Flight Ground Interface Control Document (FGICD) is typically classified at the project level, the requirements that it covers should be allowed to stretch across all project levels to prevent this duplication and minimize the V&V burden. It is important to note that in order to effectively spread the FGICD requirements across the project levels the EEIS engineer needs to become a part of the L3 and L4 design teams early (Phase A/early-Phase B) in the project development [4, 11].

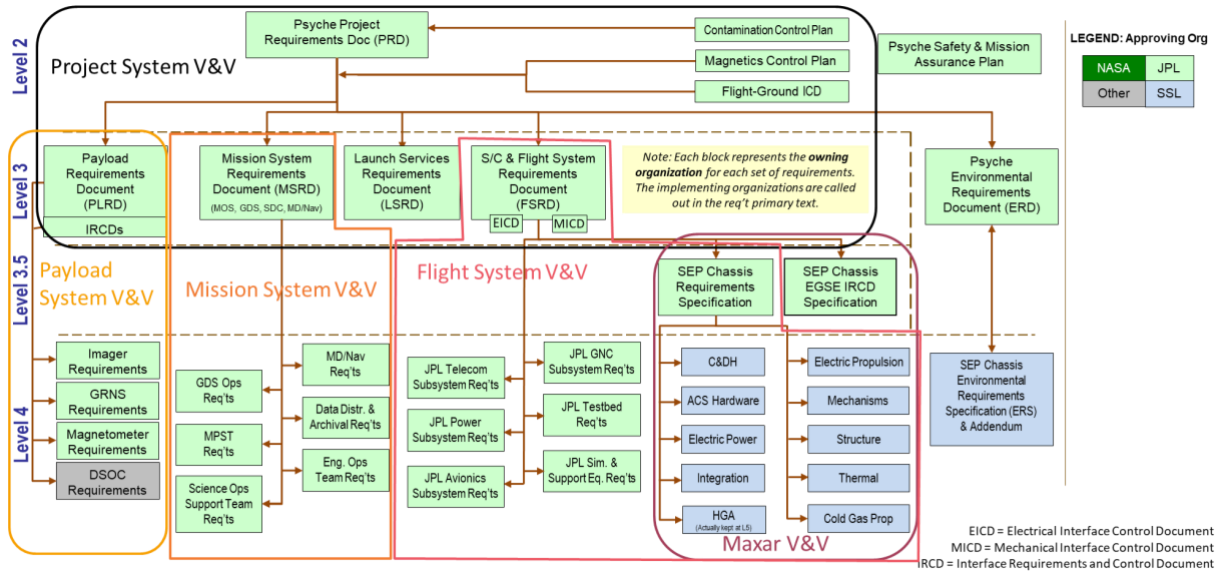


Fig. 7. Project Requirements Architecture & Flow Down

2.3 Test Types

When planning the V&V program there are several different types of tests that need to be utilized to allow the program to fully confirm that the system that was built both matches the design that was created for the mission, and confirms that the objectives of the mission will be met. These tests can be broken down in the following ways: Subsystem tests, Flight Software tests, System tests, Environmental tests, and Validation tests. Each of these tests provide valuable insight into how the system operates on the ground and how it will operate in flight. Subsystems tests are primarily used to confirm that the subsystem hardware matches the subsystem specification and are used to verify that all of the signals applied to that hardware produce the desired results (including timing, voltages, etc.). Flight Software testing is focused primarily on the interactions of the Flight SW with its environment to confirm that the commands, channels, data products etc. all interact in the manner expected. System testing takes this one step further, testing the flight software with all of the flight hardware in a combined but controlled environment. Finally, environmental and validation tests are done in as flight-like manner as possible, utilizing the flight hardware with the FSW, and operating the spacecraft as flight-like as possible.

2.4 Test Execution Venues

The test venues that Psyche used match up similarly well with the test types. For the Subsystem testing the venue was a laboratory bench top, Flight Software testing was a software-based model of the flight system, The system level testing could be accomplished in several venues including the flight software testbed (FSWTB), which consisted primarily of an Engineering Model (EM) of the Psyche Compute Element (PCE) and simulated interfaces, the Flight System Testbed (FSTB), which included EMs of most of the spacecraft hardware and could be configured to run with two PCEs allowing for fault protection and cross string testing to occur, finally some of the system testing could only be accomplished on the actual flight hardware due to limitations in the FSTB. The majority of the validation testing was accomplished on the flight system itself although a few tests needed to be run on the FSTB due to the physical limitations of the flight system. All of the environmental testing was accomplished on the flight system, in the different environmental test facilities at JPL.

2.5 EEIS Phased Development & Test Plan (PDTP)

The overall EEIS development and test program defines EEIS scope (what is and is not EEIS), and defines what EEIS testing needs to be done. That test planning is captured in EEIS PDTP. From there, the EEIS engineer analyzes objectives of tests in other test programs and, wherever possible, identifies existing tests to be part of the EEIS test program. Where no other test program satisfies EEIS testing objectives, the EEIS engineer creates a new test.

The EEIS PDTP is an EEIS team deliverable prior to beginning the planning and execution of system level tests for the purposes of verifying EEIS requirements and validating EEIS functionality in a flight-like manner. The document

and associated document review establishes the scope of the verification and validation tests, identifies gaps and weaknesses in the EEIS testing scope, and is developed based on lessons learned from similar testing campaigns.

The Psyche EEIS phased development and test approach consists of a series of phases in which the project EEIS capabilities are demonstrated, implemented, and integrated in concert with the development of the project systems, i.e., the spacecraft, instrument, MOS, and GDS. Phased deliveries lead to a final delivery of the closed-loop EEIS architecture for launch. Regression testing is carried out to verify previously demonstrated capabilities.

EEIS test activities support other system phase testing, and tests can be conducted simultaneously with ATLO tests, Mission Scenario Tests (MSTs), and Operational Readiness Tests (ORTs) to maximize resource usage.

2.6 Test Plan Development

The EEIS team spent about a month writing and presenting the PDTP to peers for the Psyche EEIS testing campaign. The core purpose of the test plan was to allocate system functionality and requirements to planned tests and add tests when necessary to ensure end-to-end compatibility of the EEIS components. From this process, the team developed a nuanced understanding of each functionality that must be exercised and the teams which must be involved in each activity—a roles matrix was developed for each test. *Section 2.8* outlines the tests that make-up the PDTP.

Writing the PDTP was beneficial but by the time individual tests procedures were ready for authorship, there were often changes to the success criteria, scope, and team involvement from the PDTP due to the immaturity of the different system elements. Scope that drops off had to be replanned and was not captured in the PDTP as it only captured initial test planning at an early moment and was not a living document. A weakness of the process was the EEIS team did not have a consistent way of capturing this dropped off test scope each time it happened.

For planning at this level, creation of the PDTP was extremely helpful, even as just an initial reference point of the scope of the test campaign. For smaller test plans that have narrower scope and do not involve coordination between multiple teams, moving directly to procedure writing may be a more efficient path.

2.7 Test As You Fly Philosophy & Exceptions

“Test as you fly” (TAYF) is a phrase used by JPL, NASA, and industry to describe a rigorous application of the long-standing test principle whereby mission related functions are tested in the most flight-like environment and configuration possible. The Psyche Project testing philosophy includes the following:

- Flight versions of HW, SW, operations procedures, command sequences and support equipment should be used to the maximum extent possible, consistent with time and budget resources and safety requirements (“flight” meaning the same versions to be used during the mission).
- Hardware, software, operations procedures, and command sequences should be used in the manner in which they are intended to be used for flight.
- Hardware, software, operations procedures, command sequences, and support equipment should be exercised over a broad range of possible flight scenarios and situations and not only just the baseline scenarios.
- The flight system (Spacecraft + Payload) will be run in flight-like mission modes with flight-like transitions between modes. All key mission activities (in the form of mission sequences) will be tested in time order, minimizing time jumps as much as possible.
- FSW will be used to configure the flight vehicle into flight-like command (CMD) and TLM configurations.
- The ground data system will be used in system testbeds, Payload integration and test (I&T) in ATLO, Flight System I&T, and ATLO for generating command and mission sequences and displaying and saving telemetry.
- Post-launch operations will be conducted within the parameters tested on the ground, including FSTB operation of all critical sequences prior to uplink, flight team comprised with members with actual Psyche flight system experience, and adherence to the flight operations handbook, flight system idiosyncrasies, and flight rules/constraints documents which establish a baseline for operations.

When testing is not a practical approach, models or simulations are utilized. Great care is taken to ensure the initial conditions in a simulated environment are flight-like and that tests in the FSTB (instead of on flight HW) used for verification are performed in an identical fashion to the flight segment. For some tests, exceptions have to be made because the test or model/simulation will not match the in-flight operation due to some constraint.

For the EEIS, some exceptions are made because the scenario cannot be tested in a flight-like manner. One example is the Radio Frequency (RF) compatibility testing between the spacecraft and the DSN. This is completed using a DSN trailer connected via a cable to the telecom system in order to simulate the telecom range. The risk is that there could be a reduced data rate or an error in the Psyche link budget that results from a range miscalculation which would require longer telecom passes in order to downlink Psyche's data—passes which the project would not be able to accommodate. This likelihood of this error when using the DSN trailer is low given the history of success the DSN has in their RF compatibility tests. Further, the trailer configuration enables distance to be simulated by putting in attenuators to create a simulated distance and air link is tested to demonstrate the telecom signal can be generated without the hat and coaxial cable. Thus, the RF compatibility test configuration is an acceptable test as you fly exception.

2.8 PDTP Tests

The EEIS testing scope can vary per project. Typically, the scope covers high-level system testing of uplink, downlink, timekeeping, and operability. EEIS testing covers the following scope:

- Level 2 data interface verification and QQCL data requirements.
 - Psyche to DSOC Project data interfaces
 - Psyche to Launch Vehicle data interfaces
 - Compliance with FGICD data protocols and DSN data interfaces
 - Total data return completeness analysis
 - Downlink management (prioritization and retransmission capabilities)
 - Level 2 latency requirements
- Level 2 timing performance analysis and time interfaces
- End-to-end validation of the EEIS
 - Psyche-DSN compatibility (includes both Flight and Mission Systems)
 - End-to-end command and telemetry flow
 - End-to-end science data flow
 - Data accountability validation
 - End-to-end FSW patch and image load validation
- Verification of some lower-level flight and mission system requirements

The following were determined to be relevant but outside of the EEIS owned testing scope:

- Level 2 telecommunications analysis and telecommunications DSN compatibility
- Level 2 requirements that do not cross a system boundary as the EEIS is only concerned with multi-system data interfaces
- Level 3 flight system and mission system requirements including those related to data interfaces and QQCL characteristics of the data flow.
 - Flight System: EEIS engineers rarely interact with fault protection. While EEIS engineering includes ensuring correct data formats, selecting correct protocols to mitigate faults, and ensuring the channels necessary for fault diagnostics, the EEIS engineer is not involved in fault protection testing. Further, the EEIS engineers are not involved in stress or robustness tests.
 - Mission System: EEIS testing evaluates the operability of the system but does not directly test for operability factors and performance. Further, specific GDS and SDC testing is outside of the EEIS scope.

The EEIS test campaign includes system level tests with significant overlap in functionality. *Figure 8* illustrates the ways in which the command and telemetry data flow test and the mission scenario test for science orbits (MST-6) test overlap in EEIS functional areas. While MST-6 was intended to test for nominal science operations, completing the activity addresses science data flow testing and the accountability of uplink products and downlinked telemetry. The command and telemetry test involves using a simulation of the DSN interface to send necessary commands to the spacecraft, receive downlinked telemetry, and process the data on the ground through Psyche's mission system processes. Thus, these tests offer redundant testing of critical EEIS functions.

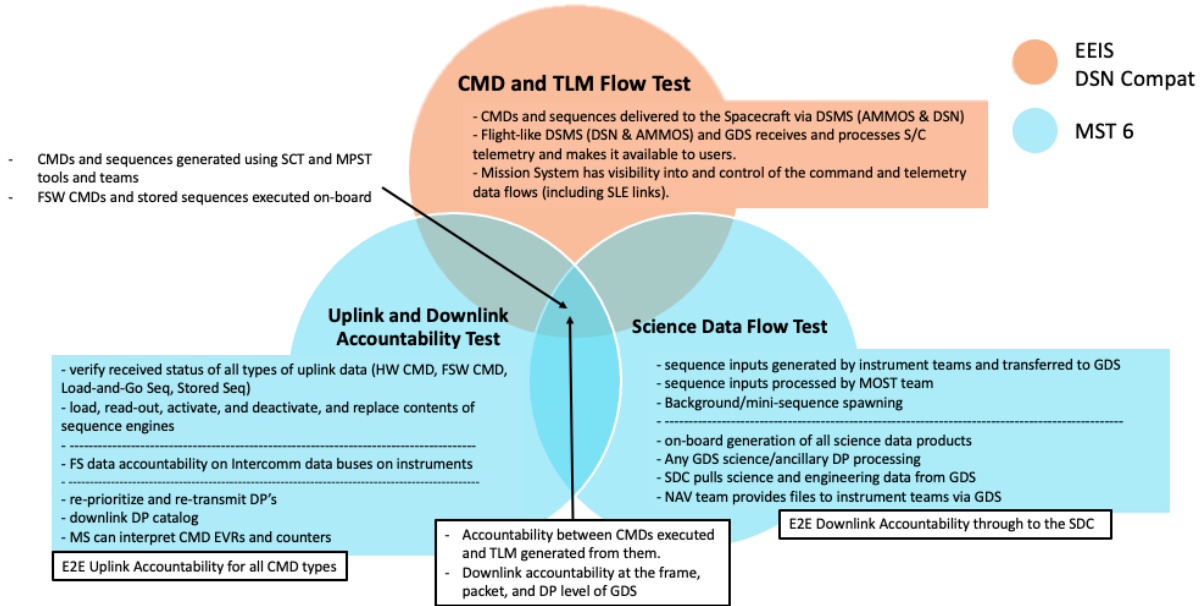


Fig. 8. EEIS Test Overlap

2.9 Testing for Operability

The ease of a mission’s operations is known as its operability. Operability is a wide topic that spans all functional areas of the project (not just the EEIS) and is heavily rooted in lessons learned from previous missions. Operability was considered throughout the mission’s development process and was regularly evaluated for comprehensive coverage of project needs and capabilities [12]. *Figure 9* illustrates how inputs from past projects and other mission concepts are ingested in the circular systems engineering project of discussing, evaluating, and analyzing operability in the design of the system and execution of flight-like tests.

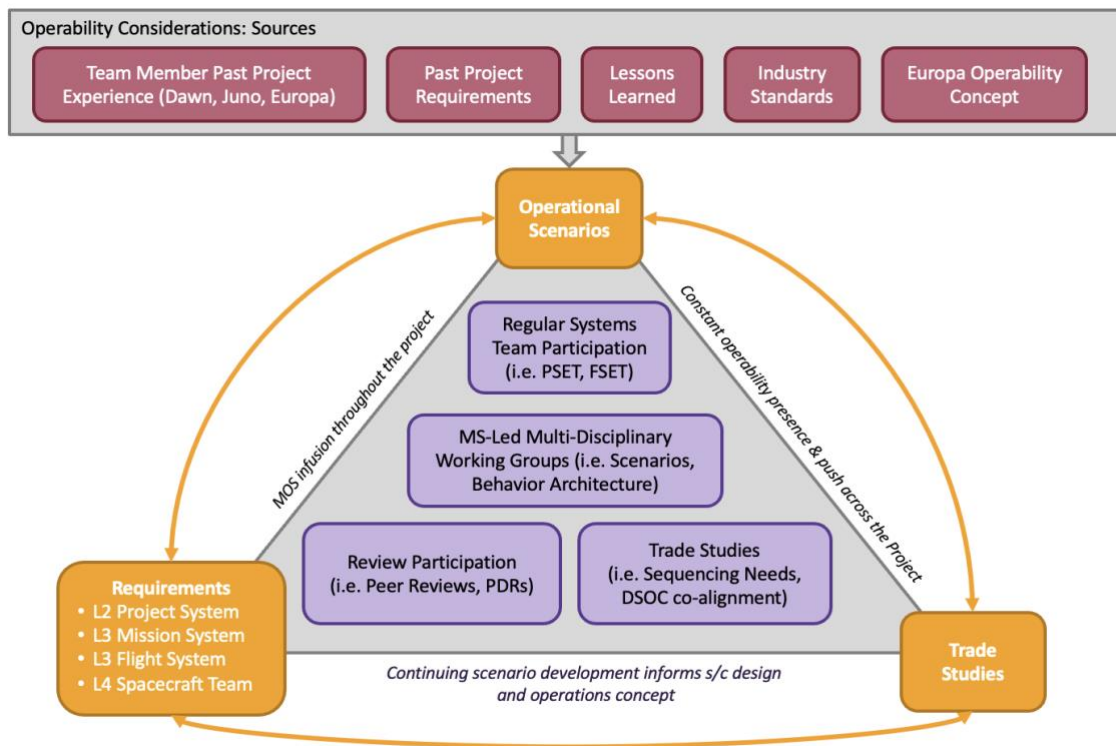


Fig. 9. Operability in the System Design

Key areas of operability needs and considerations that are also a core part of the EEIS include the following:

- System visibility is critical to ensuring operability and it is a core tenet of the EEIS to deliver complete and timely data. This visibility is achieved through the delivery of event records (EVRs), real-time EHA, and data products.
- The operations team on Psyche needs to be able to operate with a small staff and with knowledge of the EEIS in order to respond to expected and anomalous scenarios in operations.
- The operability of Psyche is also impacted by downlink constraints in the EEIS architecture. Operations will need to prioritize the necessary EHA and manage the downlink bandwidth consumption carefully to ensure they attain necessary visibility in the spacecraft's health without hindering critical science data. This is especially true in safe mode when the downlink rate is incredibly low at 10 bps.
- EEIS tests are intended to be flight-like and help illustrate the operability of the system. However, this was made difficult by flight software delays and constraints that prevented EEIS tests from being completely flight-like.

2.10 Unique Challenges

The EEIS test campaign faced many unique programmatic and technical challenges [2]. These challenges were not insurmountable but resulted in delayed tests, tests that were not flight-like in nature, and piece-wise system testing that did not fully capture the end-to-end data flow.

While there were a number of programmatic challenges (see *Section 4.1*) across the project that resulted in a new and more realistic launch date, a key issue that impacted the Psyche EEIS test campaign included staffing. The project faced high turnover of talent throughout testing. This resulted in a less experienced staff that was relatively new to JPL. This prevented the application of tangible lessons learned from past projects. Projects across JPL were left competing for talent which left knowledge and experience gaps in key technical areas on Psyche and resulted in the delay of critical software and tool deliveries. The lead EEIS engineer's time was limited due to splitting time as the flight system's MAXAR subject matter expert and later as the AVS/EEIS domain lead. Additional staff was critical to support testing. Further, the EEIS engineer had limited experience with the JPL DSN simulation and interface equipment. This was mitigated due to experience provided by GDS, Telecom, and ATLO teams

Technical Challenges in EEIS Test Plans:

- Payload Testing: Payload testing was completed in different locations and the imager was not delivered prior to TVAC testing. Further, unique FS and MS interfaces to the DSOC project requires tight coordination for end-to-end test development.
- Hybrid flight system: The split avionics design between JPL and MAXAR posed a major project risk. ATLO was the first flight harness-PCE/PDA integration venue which posed a late phase risk in the mission's development.
- New time/space partitioned FSW architecture: FSW had to budget processing resources and buffer sizes based on expected maximum data volumes. Late changes to partition resource allocation would require regression testing. Latency requirements are inherently more difficult to meet with the time partitioned architecture.
- Late software deliveries: The late software deliveries on Psyche meant closed-loop GNC was not available for testing until extremely late in the system test phase [13].
- Requirements:
 - Late EEIS FS & MS L3 requirement maturity: It was difficult to plan tests when the requirement scope was still being negotiated.
 - EEIS is a distributed, virtual system: These types of systems are especially prone to having a requirement set that does not completely describe the desired system.
- Late Deliveries: When planning, it was assumed that the HW will be ready and the SW capabilities will exist in time for the tests. It was difficult to outline what dependencies each test has. EEIS has to rely on assumed SW and GDS maturity and the master ATLO schedule. Late deliveries of software and hardware meant the team was always responding to changes, evaluating scope, and replanning tests.
- Defining Dependencies: Trying to define what is needed from venues before knowing the full test scope is tough. It is also challenging to communicate those requirements to venue teams. Institutional knowledge of the SSE and GDS capability is challenging to access. The lack of accessible institutional knowledge, clarity in capability, and lack of documentation on things like timestamping and venue capabilities made it difficult to plan and execute the EEIS tests.

3. EEIS V&V Execution

3.1 Uplink & Downlink Data Accountability

Uplink (U/L) and downlink (D/L) data accountability is tested for during DSN compatibility testing as well as during MST-6.

Uplink: The objective of the uplink portion of the data accountability test is to demonstrate that science command and sequence inputs can be properly generated by the instrument teams, transmitted from the remote sites to the GDS, used to generate Spacecraft commands and sequences by the Mission System teams, uplinked to the Spacecraft, and received and executed on-board. Testing during ORTs will also demonstrate background sequence and science mini-sequence building processes.

Detailed objectives include:

- Verify Psyche GDS Forward SLE uplink interface to DSN
- Verify the telecommunications subsystem locks to the DSN's uplink carrier frequency and subcarrier frequency and demodulates commands at all uplink rates
- Verify uplink data formats match FGICD (codeword, frame, CLTU, session, file)
- Test using the assigned Psyche spacecraft IDs (SCIDs) for command

Downlink: The objective of the downlink portion of the data accountability test is to characterize the spacecraft's housekeeping (HK) data generation rate, create all science and ancillary data product types, demonstrate that the mission system is capable of receiving, processing, and forwarding all data to the SDC and operations teams.

Detailed objectives include:

- Downlink using all legal rate and CADU combinations including carrier only safe-mode
- Use MOS-generated commands to change the downlink rate and perform flight-light rate stepping
- Use the assigned Psyche SCIDs for management of telemetry, and radiometric data
- Verify Psyche GDS downlink SLE interface to the DSN including real-time and complete telemetry services
- Receive SLE frame inventory reports from the DSN
- Verify telemetry formats match FGICD (CADU, frame, packet, PDU, and certain user data fields)
- Test simultaneous uplink, downlink, and ranging over RF
- Downlink TC reference frames and packet by command and have these ERTs timestamped by the DSN for later time correlation VAs

3.2 DSN Compatibility Test & TLM Flow

The fundamental underpinning that allows the Psyche mission to make full-use of the available DSN services is its use of CCSDS TC and AOS space data link layer standards. Psyche's FGICD is written to be compatible with the Deep Space network's modulation, coding, and framing capabilities such that the project can easily integrate with the DSN ranging, DDOR, commanding and (virtual channel) VC frame services, both online and timely.

The EEIS V&V team accomplishes DSN compatibility testing in three venues provided and staffed by the DSN: DTF-21 (a testbed-like test facility near JPL), CTT-22 (a DSN emulator in a trailer), and MIL-71 (a DSN emulator at Kennedy Space Center). The scope of compatibility testing includes SLE interface testing with the Psyche GDS (all venues), uplink and downlink continuity testing (all venues), and time correlation testing (partially tested in CTT-22 & MIL-71). The telecom subsystem team tests the ranging, delta DOR, and telecom subsystem performance (CTT-22 and MIL-71).

The Psyche mission successfully completed CTT-22 testing in July of 2021 and MIL-71 testing in May of 2022. Following CTT-22 several small data format bugs remained to be corrected. Following the MIL-71 testing in May of 2022 a SDST hardware anomaly and a time correlation bug in the FSW remained to be corrected.

3.3 Science Data Flow & Processing Test

The science data flow and processing test was conducted via a MST which are phase-driven ATLO tests that demonstrate, prior to launch, functionality of critical flight system capabilities. This test exercises the interaction

between flight hardware, flight software, and flight-like sequences to validate system performance in critical mission scenarios.

MSTs included nominal and off-nominal launch and cruise scenarios. The key MST to cover the science data flow was known as MST-6 and tested an Orbit B nominal scenario. Flight-like sequences were used to configure for HGA communications, power-on instruments, configure for LGA communications, perform imaging, and configure once again for HGA communications. During the imaging portion of the scenario, recorded data is accumulated and is fully returned in the final HGA comm activity.

MST procedure development was led by the project phase leads with support from ATLO, flight system, payload system, EEIS, and mission system. An ATLO test engineer is assigned to each MST. One limitation is that this MST execution was done with open-loop GNC control due to delayed GNC capabilities.

3.4 Deep Space Optical Communication System Testing

The DSOC EEIS Test was intended to demonstrate and verify DSOC's data flow in relation to the overall Psyche system. This end-to-end test demonstrates that the Mission System can configure the Flight System to transmit low latency DSOC telemetry, that DSOC can receive Psyche telemetry (simultaneously with the SDST configured for DSOC-only downlink), demonstrates that Psyche can retrieve DSOC data that has been uplinked (optical link not tested in this test), and demonstrate that the Mission System can downlink all the data collected by the DSOC instrument during an opportunity with the required latency.

The overall data flow and interfaces in this test is illustrated in *Figure 10* with unused interfaces greyed-out. These key goals are outlined in the following objectives.

Detailed objectives include:

- Demonstrate the ability of the Mission System to configure the Flight System to transmit low latency DSOC telemetry during a DSOC opportunity and deliver it to the DSOC MOS
- Demonstrate the DSOC instrument can receive Psyche telemetry through the telecom interface (TIF) card simultaneously with the primary SDST at DSOC-supported downlink configurations
- Demonstrate that the DSOC instrument can receive Psyche telemetry with the TIF configured for DSOC-only downlink communications
- Demonstrate that the Psyche spacecraft can retrieve uplinked DSOC data via optical link (the optical link portion of this test does not need to be carried out).
- Demonstrate the ability of the Mission System to downlink all the data collected by the DSOC instrument during an opportunity with the required latency.

Out of Scope:

- DSOC MOS and Psyche MD/Nav Interface
- Optical Link Tests (this testing occurs within the DSOC project scope)

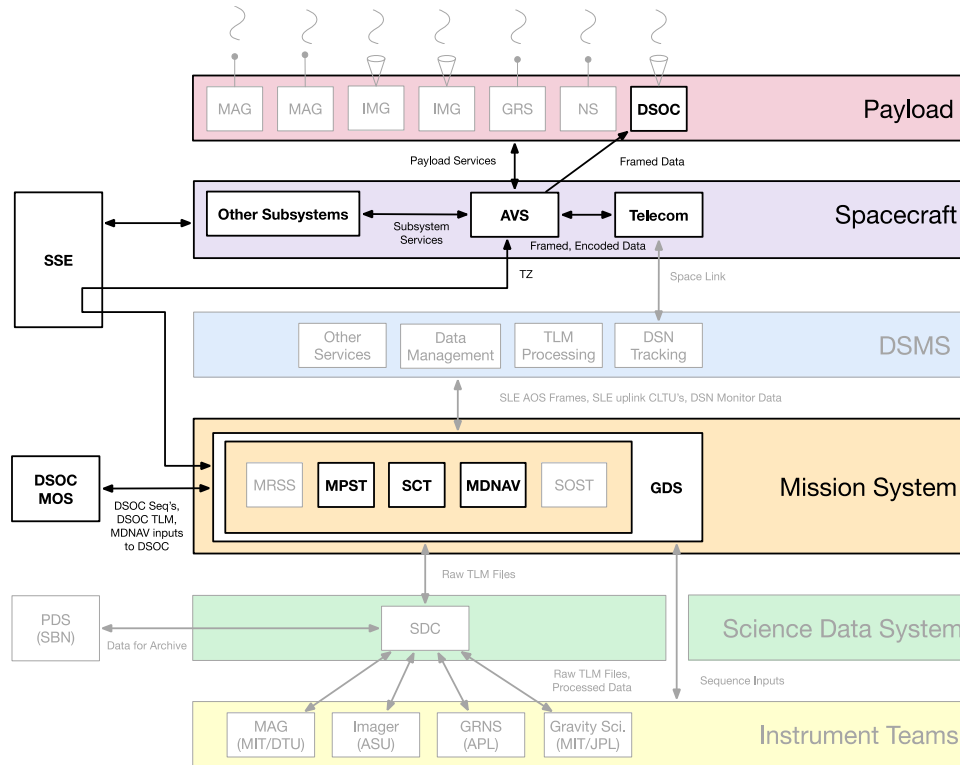


Fig. 10. EEIS DSOC Data Flow Test Interfaces

3.5 Timekeeping

Psyche maintains Barycentric Dynamical Time (TDB) time knowledge on-board the spacecraft and Spacecraft Clock (SCLK) time knowledge on the ground. The use cases requiring accuracy of one of these forms of time knowledge are (1) on-board TDB knowledge for spacecraft pointing control, (2) on-board TDB knowledge for DSOC fine-pointing, (3) ground Spacecraft Clock (SCLK) knowledge for reconstructed pointing, and (4) ground SCLK knowledge for control of on-board event execution. Different use cases drive time knowledge accuracy at different phases of the mission. The EEIS engineering team is responsible for creation of time budgets for each phase of the mission which sub-allocate time knowledge error and ensure the required time accuracy can be met through a bottoms-up approach. The verification and validation of the timekeeping budgets is part of the EEIS PDTP, though verification of certain elements specific to the spacecraft avionics or mission system are delegated to those teams [2].

3.5.1 Time Correlation

Time Correlation (TC) provides a system mechanism to correlate the time of epochs or events between the SCLK time and the ground time—Universal Time Constant (UTC)—to meet the time accuracy necessary for performing flight/mission operations and for processing telemetry into science products. A “reference” telemetry frame is real-time transmitted from the spacecraft and a subsequent TC Packet provides the SCLK value when it was transmitted. By removing the one-way light time (OWLT) between the probe and Earth from the Earth Receive Time (ERT) of the reference frame, and after other small adjustments, a pair of SCLK-UTC correlation timestamps is generated. All SCLK-UTC pairs are plotted on an x-y plot to generate a map between UTC and SCLK as the mission progresses.

A key early learning from the TC V&V on Psyche is that accuracy measurements of the TC process are only as good as the test equipment. Early on, a new data flow program for the test equipment that applies ERTs to incoming frames had to be developed by the vendor in order to enable necessary testing.

A second learning during TC V&V was that Psyche FSW was heavily customized even in areas where the heritage FSW was mature. While the generation of TC packets is a JPL heritage FSW capability, initial testing revealed mismatches between reference frames and SCLK time tags within the TC packets. While a FSW bug fix resolved the issue, this find reinforced the importance of testing basic functions early in the phased development of the EEIS.

3.5.2 *Thermal Vacuum System Test*

The Psyche Thermal Vacuum System (TVAC) Test serves the primary purpose of validating the thermal model and ensuring the spacecraft components can be maintained within their allowable flight temperature ranges by the thermal control software and devices (heaters, louvers, heat pipes, and radiators). A secondary purpose of the test is to assist the EEIS team in understanding the characteristics of the timekeeping system under dynamic and extreme thermal environments. Within this secondary purpose, two goals of the EEIS PDTP were partially satisfied by the TVAC test.

(1) The SCLK oscillator thermal stability, measured in units of ppm/°C, was characterized on one PCE for much of its expected temperature range in-flight. The Psyche mission operates with a cold standby PCE, i.e., the on-board computer which can be operated simultaneously with the prime PCE in “online” mode. Unfortunately, the second PCE oscillator thermal was not characterized for as wide of a temperature range due to a deviation from the test procedure for an unrelated anomaly. PCE unit TVAC data had to be substituted for the second oscillator.

(2) The Clock Adjust Values (CAVs) which are used to change the rate of SCLK for each PCE can be validated by TVAC. These values guarantee the prime and online PCE oscillators have similar rates such that communication between the prime and online PCEs is not disrupted by large time synchronization adjustments by the online PCE. The online PCE oscillator often experiences lower temperatures since the oscillators are co-located within the PCE chassis with the processor and the online PCE is given fewer computational tasks than the Prime. TVAC is a perfect test to validate the chosen CAV values allow for seamless cross-string communication in hot and cold mission scenarios. However, Psyche’s avionics V&V was not far enough along to have selected CAV values prior to TVAC. This added a significant amount of analysis that had to be completed in addition to the EEIS team’s primary role of verifying and validating the mission time budgets.

3.6 *Launch Vehicle Compatibility Tests*

This command and telemetry test flowed data through a SpaceX payload launch adapter (PLA) and LV umbilical simulator to the GDS. The simulated umbilical had realistic impedance values which illustrates that the physical cable can accommodate the expected data rates and that the Psyche had compliance with the launch vehicle ICD. Post-MST data analysis proved that the expected Spacecraft housekeeping data generated when the spacecraft is on the pad fits into the available bandwidth of the LV umbilical with margin.

3.7 *FGICD Compliance Assessment*

Assessing the requirements in the FGICD can be challenging depending on how those requirements were written. Generally speaking, the bulk of the requirements in the FGICD are intended to be verified by lower-level system and subsystem activities, and the role of the EEIS Engineer is to audit that verification evidence and ensure that the EEIS itself has been sufficiently verified. After all of the relevant evidence from flight and mission system verification activities has been assembled together from the perspective of the EEIS, gaps in verification coverage may be identified—when this occurs, the EEISE fills those gaps by generating the remaining necessary verification evidence (either directly or through guidance provided to the original lower-level implementers who generated the original verification evidence). Common causes for these gaps are project scheduling needs which result in flight system and mission system V&V occurring out of phase with one another, or when either the flight system or mission system verification evidence was generated using non-flight-like processes, tools, inputs, configurations, etc.

On Psyche, the FGICD requirements were written directly on the organizational entities that were expected to implement and verify said requirements. These implementing systems were clearly identified in the metadata for these requirements which effectively communicated the verification responsibility. This approach led to the successful verification of lower-level requirements with minimal gaps in tested functionality.

Beyond assessing compliance with FGICD requirements, the EEIS Engineer also determines the implementation of the specification information in the FGICD that is may not be covered by requirements. This effort is managed differently on each project. Psyche chose to encapsulated this additional scope by levying a general compliance requirement on the project system. Then, anywhere that a mismatch between the FGICD specification and the as-built system was identified, the impact and risk of the variance was assessed, and the FGICD was updated to match the as-built system (as opposed to correcting the as-built system to match the FGICD). These disconnects, as well as the efforts taken to correct them, were identified in the closure package that was used as evidence for the project system FGICD compliance requirement.

3.8 Data Return Completeness Analysis

The EEIS requirements to return a certain percentage of all the data produced are difficult to prove through test or analysis for an entire mission’s performance. There are numerous components in the EEIS that can impact data completeness from the point of generation to the point of mission system archival. These points of potential data loss can occur at nodes where memory exists or across links between memory nodes. These data links and nodes are depicted in *Figure 11*. Most missions do not write completeness requirements due to how challenging they are to prove. While tests will show the volume of data generated versus the volume returned, the analysis required to understand data completeness must also account for end-of-life memory degradation, DSN performance, and likelihood of data loss. Further, Psyche has retransmission capabilities which means data lost across the flight to ground interface can be re-requested. Thus, these requirements were closed with a mix of analysis and test performance by assuming worst case, nominal, end-of-life performance. While the requirements are challenging to prove as a performance requirement, they are effective at forcing data loss analysis across the entire EEIS.

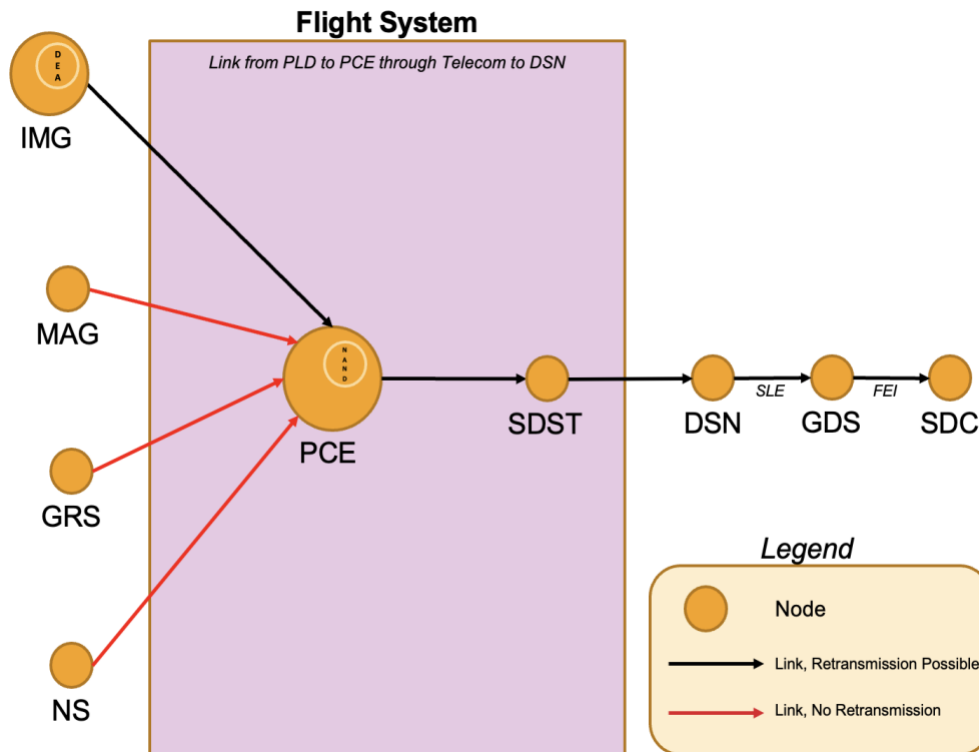


Fig. 11. Data Flow Nodes and Links

3.9 Housekeeping & Ancillary Data Volume Analysis

Housekeeping (HK) and ancillary data (i.e., engineering data or EHA) requirements ask the EEIS team to analyze test data to determine the expected HK data rate and ensure that it does not exceed the data budget allotment. This analysis also, inherently, asks what the expected science data volume is to ensure the combined bandwidth of necessary EHA data and science data do not exceed the allotted downlink bandwidth. Psyche is a downlink limited mission which makes this analysis especially important as the project will need to actively manage engineering data production in order to maximize science return.

This analysis was done with flight-like system test data from the most recent ATLO system tests and MSTs. The goal was to gauge the data volume and data rate in the highest stress cases in both cruise and science operations and determine if the data budget closes with that best estimate. Over the course of this analysis, it was discovered that the science products were larger than originally planned but that the margin in downlink communication passes over the course of the mission accommodate all of Psyche’s necessary science and engineering data as long as the channelized telemetry in the EHA products are carefully managed.

4. Challenges

Psyche faced a number of challenges during its development and testing lifecycle. These challenges were both programmatic and technical and impacted all levels and areas of the project. The overall impact resulted in the Psyche Mission's missed 2022 launch opportunity. These challenges are a combination of findings from NASA's Independent Review Board (IRB) and challenges the EEIS team on Psyche faced first-hand [14].

4.1 Programmatic Challenges

Management, organization, and communication were common problems across the project but were not addressed until late in the test campaign. Psyche often struggled with siloed teams and a lack of communication up and down the organization. The culture and management led to concerns and risks not being communicated up the chain and resulted in a delayed response to issues and a lack of resources to solve those problems. Concerns must be elevated and emphasized in a timely fashion and with adequate resources.

High turnover at JPL and on the project, competition for talent at JPL, and a lack of experienced personnel on the project contributed to many of Psyche's challenges and delayed deliveries. The lack of available and knowledgeable staff led to a high workload, burn-out, and turnover.

COVID-19 undoubtedly altered the work environment and relationships between teammates [15]. Testing and development in the pandemic and adapting to hybrid-work may have hindered team communications.

Information on the project was difficult to access and the lack of accessible, clear, updated, and timely documentation made it difficult to scope work, plan tests, understand interfaces, and generally resulted in additional technical challenges.

Vendor relationships and the shared avionics architecture with MAXAR was a challenging effort and interfaces between the major systems needed to be correct, complete, and adequately documented and then reviewed by experts.

4.2 Technical Challenges

The implementation and testing of Psyche's EEIS faced a number of technical challenges.

The project architecture involved a unique and difficult hybrid FS with split AVS shared between JPL and MAXAR. This design impacted integration and presented communication and interface testing challenges.

There were unique data interfaces to each instrument which required additional testing as each instrument had a unique data link layer (and often physical layer). This increased the overall test scope as there were a greater variety of requirements that had to be closed by the instrument and spacecraft teams. Additionally, there were unique Flight System and Mission System interfaces to the DSOC Project which required tight coordination with DSOC Project for end-to-end development and testing. The accommodation of technology demonstration was an additional testing scope on top of the standard EEIS tests.

A number of technologies that are new to JPL were introduced on Psyche. These new technologies required additional resources for more in-depth testing as there was limited heritage to rely on. New time and space partitioned FSW architecture meant the FSW had to budget processing resources and buffer sizes based on expected maximum data volumes. Late changes to partition resource allocation require regression testing. Latency requirements became more difficult to meet with a time partitioned architecture. Also, new GDS SLE interfaces to the DSN mean that early testing of the SLE service with GDS was necessary before end-to-end tests involving the FS.

The Psyche project faced a number of limitations on its test venues and data analysis methods. Slips in deliveries of a key software functions resulted in late GNC and reduced how flight-like system level tests were. Further, the actual workstation test set (internal simulation program) did not operate in real-time and required significant amounts of time to run test procedures and produce viable data to be analyzed. These venue and software limitations utilized precious time and left system tests with non-flight-like configurations.

One of the primary technical challenges on Psyche and on the EEIS's ability to comply with the data budget is that the mission is downlink limited and requires managing engineering data production in order to maximize science return.

This requirement led to significant analysis and V&V efforts to prove the engineering data production could be effectively managed and that the data budget, over the course of the mission, would be respected.

5 Lessons Learned

Psyche's EEIS V&V efforts were educational and highlighted a number of lessons learned that can improve the EEIS's development, implementation, and testing. These lessons can also be applied to the improvement of other flight project practices at NASA, JPL, and other institutions.

5.1 EEIS Engineering Discipline

The scope of the EEIS and the responsibilities of the EEIS engineer/team are redefined on each project. This is often dictated by the scale of the project, processes established by Mission, Flight, and Project System teams, and the discretion of the EEIS lead engineer. Some structure around the scope of the role to ensure the responsibilities focus on critical project needs and are balanced with the staffing bandwidth is necessary to ensure the successful delivery of the EEIS.

EEIS staffing and adequate knowledge transfer have been an additional challenge. The role is incredibly comprehensive—requiring knowledge of various test process, technical interfaces, JPL heritage and lessons learned, and time architectures. Traditionally, the role attracts experienced staff members who have prior subsystem experience. Training early career engineers into this role has been a recent effort and poses its own challenges as the EEIS leads are often spread too thin to be able to mentor and educate. Additional training resources and splitting early career EEIS engineers' time between a mission or flight system role and the EEIS team to expose them to other relevant concepts, mentors, and resources can help mitigate some of these challenges.

JPL's approach to the EEIS engineering discipline is distinct from other NASA centers and aerospace institutions. Elsewhere, the role is typically divided across the different subsystems without a singular point of contact overseeing the entire end-to-end flow or focusing on system interface tests. That approach places the responsibility on subsystem leads to work and test interfaces but leaves a gap in system operability and system validation testing in a flight-like way. The approach JPL takes with the EEIS has its merits and advantages and should become a more standard practice in the implementation of the flight-ground protocols, system-level communications, data accountability, and scenario testing.

The scope of the EEIS includes U/L and D/L among numerous other tests. While the role of the EEIS engineer is advantageous to a project, many subsystem leads could conduct portions of the EEIS test campaign to mitigate workload concerns—especially on U/L and D/L tests. Psyche had a combined L3/L4 V&V. It would have been beneficial to use a delivery review as a gate to verify U/L and D/L issues prior to delivery. However, this was not possible due to staffing issues that led to a combined L3/L4 approach. Domain structure were used to address the blend between L3 and L4 but was introduced too late in the development process.

The PDTP has numerous benefits in helping define the purpose of EEIS testing and drawing boundaries around the scope of EEIS tests. While it is useful to begin thinking about the test campaign early on, the timing of the plan's development means it lacks details. It is difficult to gauge which tests will be dependent on what software and hardware capabilities, which ones have redundant scope with other system-level tests, or how flight-like the tests will be at the time of execution. The PDTP process can be improved by revisiting the plan over time to identify when key software or functional changes impact tests.

Numerous EEIS requirements are broad in scope and difficult to V&V as they are intended to fill gaps in functional, flight-like testing. This aspect presents a natural challenge in approaching EEIS verification and validation testing, analysis, and specification compliance. In the instance of FGICD compliance assessment, the EEIS team found it effective to write the interface requirements directly on the system intended to perform the verification of those requirements. This minimized requirements duplication and increased the likelihood that those requirements would be implemented and verified as intended. This was largely successful through the use of requirement metadata and tools that notified specified responsible engineers. This metadata should be kept current to allow the EEIS team to more efficiently assess lower-level verification evidence and minimize project level verification efforts or duplicate efforts to close FGICD requirements and scope.

5.2 V&V Practices

The Psyche V&V team had numerous V&V practices/policies that cannot be discussed here due to length. However, there are several key areas that might be helpful for future EEIS & V&V teams to think about when planning and executing EEIS V&V programs. Requirement traceability and duplicative requirements occur when forcing the entire FGICD to be captured at the project level. Additionally, load switching V&V structures mid-stream can have a negative impact on the V&V teams' ability to execute and complete V&V tasks.

In addition to requirement traceability, it is important to be aware that in the heat of testing/software development, lower-level requirements can mistakenly be closed with evidence that may become invalidated by future Engineering Change Requests (ECRs) or FSW updates. To address this, it is recommended that the project have a process for reviewing closed requirements (audits), opening requirements with outdated verification evidence to update their closures, and most importantly that the EEIS engineer remain vigilant to ECRs/FSW changes and identify appropriate regression testing as needed.

As with all systems, managing the EEIS V&V schedule is key to ensuring all the appropriate tests are completed and in a time frame that matches the availability of the Testbeds & ATLO schedules. This is particularly important when the team needs to request additional support to keep up with and finish the test program. If the lead EEIS engineer becomes too overloaded to maintain the EEIS schedule then it becomes very difficult to show management precisely where additional help needs to be provided. Again, the Domain structure was introduced to better allocation test venue resources to test activities, major problems in SW and HW, and testing capabilities along the critical path for system tests. However, the late phase introduction of the structure meant that the EEIS test schedule and awareness of the venue schedules and capabilities fell on the EEIS team.

5.3 Programmatic Practices

The Psyche IRB includes a thorough breakdown of programmatic challenges that impacted the project. There were, however, some additional programmatic efforts that benefited the EEIS and some lessons learned that can be applied to future missions.

Staffing and knowledge transfer were a challenge on the project overall, EEIS engineering included. Some of the workload challenges on Psyche and need for technical mentoring within EEIS engineering at JPL were addressed by adding EEIS engineers to the project for the system test phase. The addition of one early-career, full-time EEIS engineer and two part-time EEIS engineers with specialized knowledge and prior experience enabled the EEIS team to adequately cover necessary scope, respond to requests and issues, and focus on high priority tasks. Additionally, the presence of a Deputy PSE who had prior EEIS engineering experience provided the EEIS team with critical peer review and feedback for major U/L, D/L, compatibility, and science data flow tests. In the future, EEIS teams should continue to consist of a lead engineer with some level of support from early-career and experienced engineers to ensure EEIS knowledge transfer and reviewers. Further, regular meetings between the project's management and the EEIS team are a necessary part of providing resources to the EEIS team to conduct their tests. This line of communication should be prioritized by project management due to the critical nature of the EEIS to Psyche's mission success.

And, again, the domains structure and domain leads were introduced too late in the project to respond to and address management challenges and try to help streamline system testing. The project should have either started with domains or not introduce them because switching the process caused miscommunication, impacted staffing, disrupted team expectations, and cost the project additional time and resources.

5.4 Best Engineering Practices

In addition to the specific EEIS, V&V, and programmatic lessons learned suggested, there are a number of best practices that could have helped mitigate challenges on the Psyche project and should be applied on other projects.

Documentation was often lacking on the project. Documentation often failed to communicate necessary information or simply did not exist. JPL does not have a consistent, institutional culture around documentation and each team or individual often approaches these documents and internal articles differently. To make matters more challenging, each mission may have its own methods and tools for documentation. These factors mean that documents on different missions may cover different things and the documentation itself may be hard to access. For example, not all projects require EEIS concept documents or PDTPs. Also, not all projects have document lists that allow team members to search and find project-relevant documents. And, in some cases, the institutional tools are outdated and original items

from past missions are inaccessible. Documentation should be built from the ground-up and cross-referenced. Some teams encourage an ecosystem of informal knowledge capture articles and include this as part of the job expectation and performance evaluation. This practice makes documentation easier to generate and access, and reinforces how critical the practice is to mission success.

Psyche engineers had a tendency to initially trust heritage products and systems. This assumption led to the discovery of issues later on as certain heritage items (i.e., time correlation SW, uplink and downlink SW, etc.) had bugs and required PFRs and additional V&V. The institutional practice of adopting heritage technology should require some lower-level testing to validate experience performance in order to avoid late V&V.

6 Conclusion

The Psyche Mission's EEIS PDTP was developed to help define the EEIS test scope and approach for its V&V. Core elements of the EEIS V&V scope include data flow and accountability across the system, timekeeping, uplink and downlink compatibility with the DSN, and analysis for FGICD compliance, data completeness, and data budget analysis. The team faced a number of technical and programmatic challenges in an effort to test the EEIS core functions and was forced to adapt test plans due to delayed capabilities, venue limitations, staffing challenges, and late phase issues. This required the team to re-evaluate dependences for each test and how flight-like the tests were at the point of execution. The V&V planning and execution process for the EEIS could have been improved through EEIS discipline, V&V process, programmatic, and institutional best practice improvements.

The EEIS engineer's role is to a critical function on a flight project as they help bridge the gaps between major data interfaces and provide consistent oversight on the full system's functionality and operability. Improving on the discipline, developing talent, identifying weaknesses in the EEIS on the project, and recursively visiting EEIS test plans will all improve on the EEIS V&V outcome.

V&V practices and policies can be improved to prevent requirement redundancy and improve on traceability, audit requirements to prevent ECRs and other late-phase developments from invalidating earlier V&V work, and support EEIS test dependency analysis to better manage resources and support high-level communication tests.

Projects and institutions should also carefully consider the balance between staffing and the workload. The EEIS scope can grow rapidly without careful consideration of the core deliverables needed. Staffing should both help develop talent for future missions and have the support of experienced EEIS experts. Projects should also implement attainable documentation standards that are accessible and useful to the team to help inform on complicated EEIS topics and interfaces with reasonable updates as required. Further, projects should decide on their project management structure for V&V early on so that the test phase is not disrupted by organizational changes and management communication issues.

These challenges and lessons learned in the implementation and testing of the Psyche EEIS help inform future space missions on how to more effectively approach EEIS V&V planning and execution. The suggested improvements in the EEIS test campaign will help missions by making their system tests more flight-like, help encourage operability design considerations, address documentation and best practices, hone the scope of the EEIS test scenarios, better document the functions of this virtual system, and identify gaps in the EEIS's test coverage.

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