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SUN SEARCH DESIGN FOR THE PSYCHE SPACECRAFT

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Psyche is a scientific mission to explore the large asteroid (16) Psyche that orbits the Sun at ~3 AU. Managed by JPL, it is the first instance of Maxar's product line of geosynchronous communication satellites being repurposed for deep space. This paper presents the design of a unique sun sensor configuration for Safe Mode of the spacecraft. It enables quick, robust, and propellant-efficient safing while leveraging sensors, avionics, and algorithms that have extensive, flight-proven heritages.

INTRODUCTION

The Psyche mission was selected by NASA for flight as part of the 14th Discovery mission competition in 2017 and is scheduled to launch in 2022. The goal for this mission is to explore the large asteroid (16) Psyche (~240 x 185 x 145 km) that orbits the Sun at ~3 AU. Unlike any other body in the solar system, Psyche is a world composed almost entirely of metal and is larger than any known metal body. A mission overview highlighting key milestones and Science orbits at Psyche-16 is shown in Figure 1.

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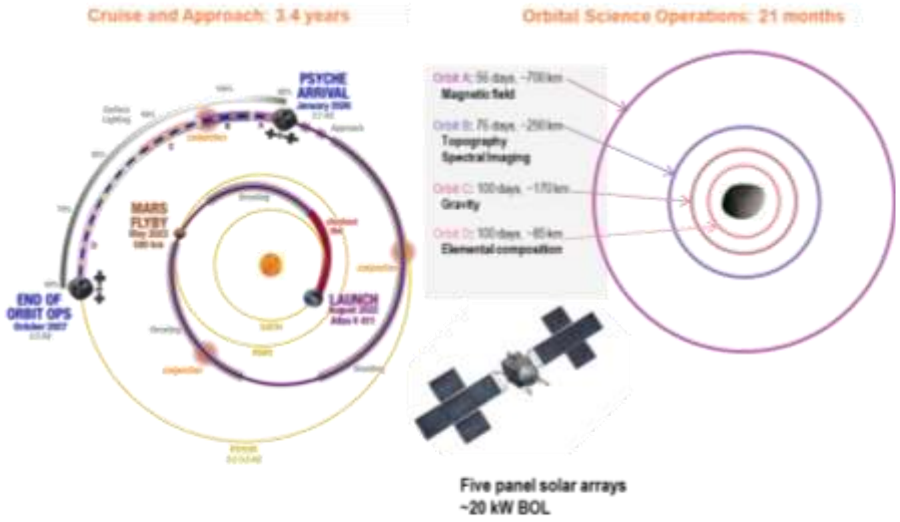

Figure 1. Psyche Mission Overview and orbits at Psyche-16

To save development cost and schedule, JPL is partnering with Maxar Space Solutions (formerly Space Systems Loral (SSL)) and procuring their standard SSL-1300 product-line solar electrical propulsion (SEP) chassis. It will be integrated with JPL's avionics and subsystems as well as with four science instruments.[1] The overall design concept and the integration of Maxar's SEP chassis with JPL components has been published in the past[2,3,4,5]. The overall GNC conceptual design described in Reference 4 has been significantly improved upon over the past year and includes the Sun Search design to be discussed in this article. Figure 2 shows the current spacecraft layout from two opposite views. The rectangular box is Maxar's standard SSL-1300 SEP chassis with solar arrays removed. The top deck accommodates two science instruments, a Magnetometer (MAG) and a Gamma Ray and Neutron Spectrometer (GRNS), along with the high gain antenna (HGA). Other instruments include two Imagers and a Deep Space Optical Communication transponder (DSOC). They are placed on each of the -/+ X faces, respectively. GNC components include star trackers or stellar reference units (SRU), coarse sun sensors (CSS), inertial reference units (IRU), reaction wheel assemblies (RWA), solar array drives (SADA), cold gas thrusters (CGT), Stationary Plasma Thrusters (SPT), and the dual axis pointing mechanisms (DAPM) used to articulate the SPTs. Note that some components such as the IRU and RWA are internal to the spacecraft outer structure and are invisible in the figure. While GNC hardware is all provided by Maxar's SEP Chassis, it is functionally driven by JPL's GNC algorithms. The current GNC functional block diagram is shown in Figure 3.

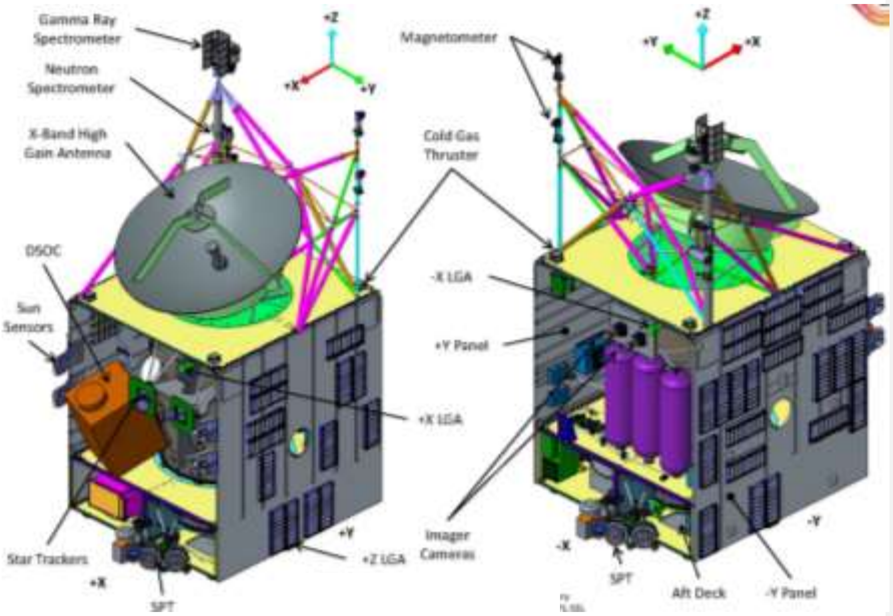

Figure 2. Psyche Spacecraft System Layout and Coordinate System

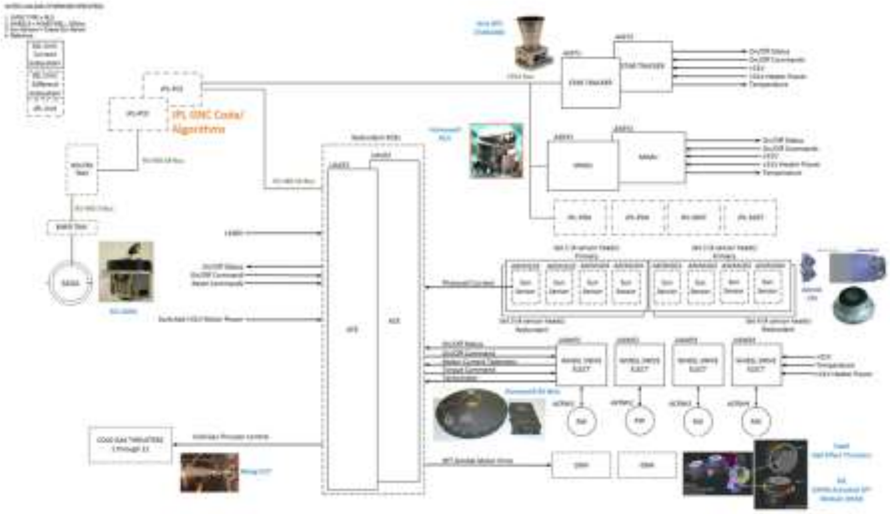

Figure 3. GNC Functional Block Diagram

When an anomaly occurs during the mission, the spacecraft enters a so-called Safe Mode to protect itself from potential damage. The design of this operational mode is particularly crucial for Deep Space missions, where ground contact with Earth is very limited, and severe faults must be accounted for.[2] Safe Mode is typically designed to turn off non-essential components to minimize power usage and point the solar arrays toward the Sun to maximize power availability. For Psyche, this is accomplished by pointing its +X axis toward the Sun and aligning the Solar Arrays to maximize power. When a flight computer fault occurs, it is powered off and a swap to the redundant one is done. Often this swap causes the spacecraft attitude information stored in the primary computer to be lost and not available to the redundant computer when awakened. It is therefore critical to perform a Sun search and slew to a power and thermally safe attitude before the battery is exhausted. Among GNC components, the coarse sun sensor (CSS), essentially a passive solar cell (photo-diode), is considered the sensor most immune to faults due to its simplicity. Inertial Reference Units are considered vital components for Attitude Determination and are usually redundant. The CSSs and the IRUs are therefore typically used on interplanetary spacecraft to find the Sun.

For the Psyche mission, the sun search design work started with the requirement definition following the process presented in Reference 5. Numerous trade studies based on a mission-profile power model were conducted. It was concluded that the worst scenario happens in Orbit D, the lowest altitude orbit with an orbital period of 4.1 hrs., when faults occur at the beginning of eclipse as shown in Figure 4. The CSS-based recovery in green happens right after eclipse when the Sun can be found. Note that there is a 10-min solar array warm-up time, when the solar array is not in full performance. Figure 5 shows various recovery scenarios (nominal vs. 37 min, 71 min, and 103 min) of battery state-of-charge (SOC) vs. eclipse durations while in the eclipse season. The blue bars in the figure are the eclipse durations during eclipse season. The battery SOC is discharged to a lower level during the eclipse and is subsequently charged back to a higher level when out of eclipse. SOC may not be fully charged prior to encountering the next eclipse. Nominally the battery is large enough for Psyche's eclipse season. A shorter recovery time prevents the battery from dipping into its low SOC state which may cause the spacecraft to enter into an unrecoverable failure. Sun search duration plays a crucial role during the recovery. Once the Sun is found, the solar arrays are pointed to the Sun to within a tolerance to allow for sufficient battery charging before encountering the next eclipse.

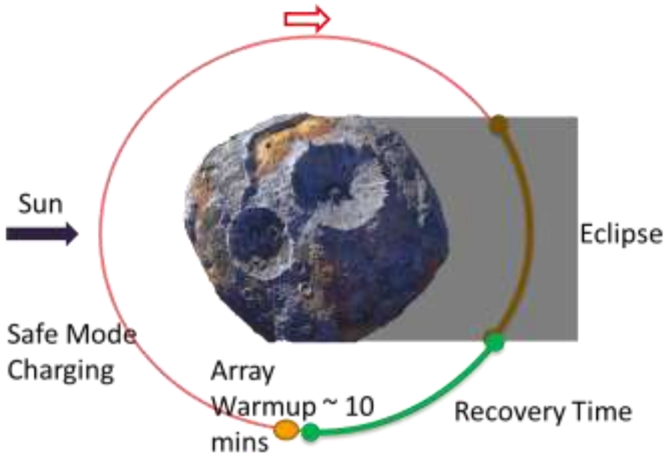

Figure 4. Power Model for Orbit D

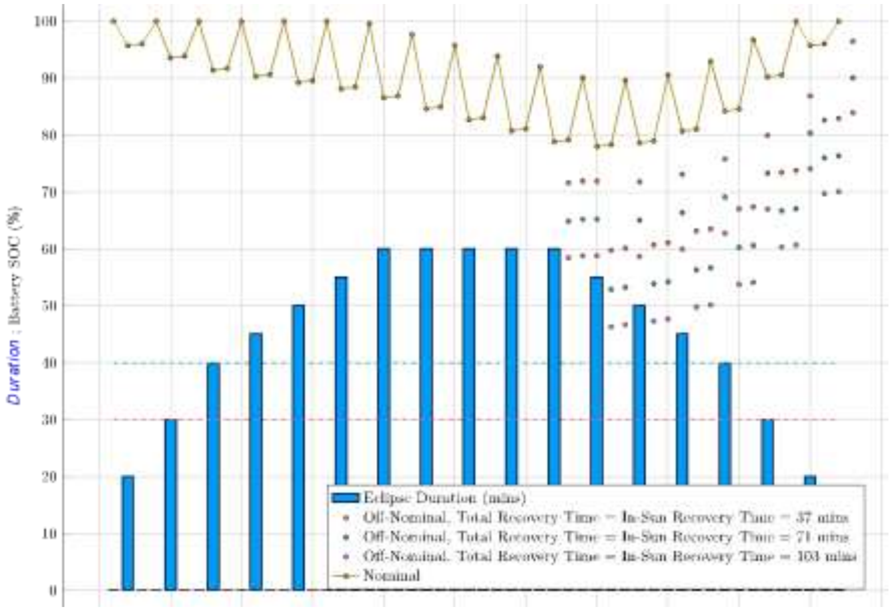

Figure 5. Eclipse Duration vs. Battery SOC with Safing in Orbit D

In this paper, the unique CSS layout and sun search algorithm design for Psyche will be presented.

HERITAGE SUN SEARCH APPROACH

Heritage Safing Sun Search approaches from both JPL and Maxar were considered for Psyche. The two organizations use different methodologies and hardware for Sun Search. Brief descriptions of each follow.

Inherited from the Soil Moisture Active Passive (SMAP) design,[3] two Adcole pyramid type CSS assemblies, as shown on the left side of Figure 6, were used in the Psyche conceptual design in Reference 4. The SMAP heritage design allowed for the determination of a S/C-body-relative Sun Position Estimate whenever 3 or more CSS heads are simultaneously lit. This condition is known as the “Sun Found” condition. Each pyramid CSS assembly consists of four individual coarse sun sensor heads, as shown on the right side of Figure 6. These sensor assemblies have the advantage of easy installation and data processing for two-axis Sun position knowledge. The limited field of view (FOV) inherent to the pyramid CSS design requires the spacecraft to perform a sequence of slews in order to achieve 4π steradian sky coverage with three or more heads and guarantee that the Sun is found.

Figure 6. Pyramid Type CSS Used in SMAP and Single CSS Head

On SMAP, a 180° Z-axis slew followed by a second 180° X-axis slew guaranteed full sky coverage with at least three simultaneously lit CSS heads. Figure 7 shows Coarse Sun Sensor coverage after completion of the Sun Search slew sequence. The orange area indicates regions of the sky swept with 3 CSS head coverage and the dark red area indicates regions swept with 4 CSS head coverage. A second set of Z and X axis slews was subsequently performed if the Sun was not found after the first set of slews due to either the S/C being in eclipse or a single failed CSS head. The total Sun Search recovery time under Reaction Control System (thruster) control was 37 minutes or 55 minutes with an eclipse when both sets of slews are performed.

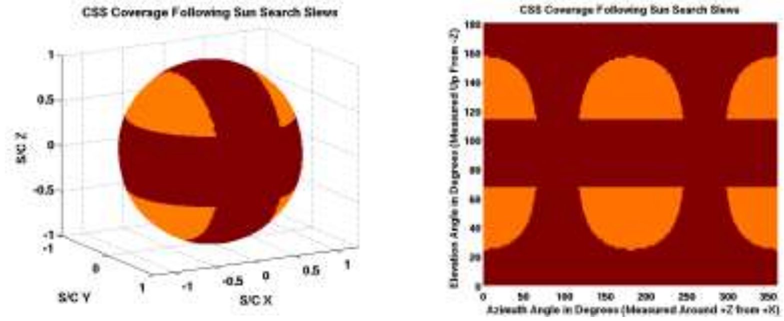

Figure 7. SMAP CSS Coverage post Sun Search Slews (no CSS head failures)

The Maxar heritage SSL-1300 bus uses six Enhanced Coarse Analog Sun Sensors (ECASS) comprised of two sets, primary and redundant. Each set consists of two sensors for the Roll (+X) /Yaw (+Z) axes and one for the Pitch (+Y) axis.

Maxar heritage with respect to Sun Search is based on performing a single axis rotation to determine and maintain Sun presence. Two ECASS are configured to span a Fan of at least a 180° FOV so that as the spacecraft rotates about the X axis, the Sun will be detected by one or both ECASSs with one rotation. Once the Sun is acquired with the Roll/Yaw ECASS, the spacecraft is rotated about the pitch axis until the Sun comes into the FOV of the Pitch ECASS. This provides successful Sun acquisition and locates the Sun along the -X axis of the spacecraft. The Maxar heritage Sun search therefore uses two slew maneuvers to acquire the Sun.

The SMAP Coarse Sun Sensor configuration and Sun Search algorithms were used as a starting reference for the Psyche proposal as it leveraged heritage algorithms and lessons learned from previous JPL missions. The use of Maxar's hardware (i.e. ECASS configuration) combined with JPL's sun search algorithms led to various trades to optimize both Sun found regions and minimize Sun search duration for Psyche.

SUN SEARCH TRADES FOR PSYCHE

The details of the iterative design process for requirement definition and the trade studies performed on sun sensor placement, spacecraft slew strategies, avionics modifications, and algorithm design are presented in the following sections.

Coarse Sun Sensor Configuration Evolution & Considerations

In general, Sun sensors are cheap, low mass, and simple attitude sensors that are used on many spacecraft to provide knowledge of the Sun's orientation. It is a good spacecraft design practice to maximize Sun sensor celestial coverage as it makes Sun search faster. This is particularly important for interplanetary missions where the spacecraft needs to have a high degree of autonomy. As such, the original coverage requirement of the Psyche Sun Sensor system was to provide 4π-steradian (full sky) Sun-found coverage at all times, with single fault tolerance. To meet this requirement, many configurations were considered.

The Psyche spacecraft is heavily based off of the SSL-1300 Bus, a geostationary (GEO) communications spacecraft design flown more than 100 times since its initial flight in 1989. Like most geostationary spacecraft, the Psyche spacecraft features two large, deployable Solar Arrays that can rotate relative to the bus about the spacecraft Y-axis via the Solar Array Drive Assemblies (SADA). Each Psyche Solar Array contains five individually populated panels deployed in a cruciform pattern. To interface and control the bus equipment used for attitude determination and control, Psyche has two Attitude Control Electronics (ACE) units, which are Maxar-built avionics boxes optimized for the SSL-1300. Each can support up to 8 photocell inputs without requiring new or additional hardware. Only one ACE is used at a time with the other serving as a cold spare.

As mentioned earlier, the baseline (proposal phase) Psyche Sun sensor architecture consisted of two Adcole Pyramid Coarse Sun Sensor Commercial Off-The-Shelf (COTS) assemblies. These assemblies were mounted on opposing ±X faces with the +X face of the spacecraft being nominally Sun-facing and the -X face of the spacecraft being nominally away from Sun in safe mode. In this configuration, each assembly can provide nearly 2π-steradian (hemispherical) Sun *presence* coverage without redundancy. Each of the two ACE's would be connected to a single Pyramid sensor assembly on each side. Redundant assemblies were then added to each ±X face and cross-strapped to each ACE to allow for either a Pyramid CSS Assembly failure or an ACE failure without loss of coverage.

The CSS design given in the proposal posed several problems to the Fault Management strategy. Specifically, the Psyche Sun-search algorithm needs three or more sensors to be illuminated simultaneously to deterministically solve for a Sun position solution. A region where three of more sensors are illuminated simultaneously is referred to as a "Sun-found" region. While the proposal CSS configuration achieved near 4π-steradian coverage with individual CSSs, it provided very little Sun-found coverage. The implementation of Sun-search maneuvers was therefore considered to supplement the small Sun-found regions. It was found that Psyche would require a complicated maneuver profile and more time than the spacecraft could tolerate in specific fault recovery scenarios. All of these challenges were drivers towards designing the unique Sun sensor configuration for the Psyche mission. The following sub-sections provide a quick summary of the trades carried out that lead to the current design.

ECASS vs Coarse Sun Sensors

The SSL-1300 Bus has heritage with ECASS. ECASS provide reduced “Sun Found” sky coverage when compared to a pyramid Coarse Sun Sensor assembly. To achieve full Sky coverage, either additional ECASS would have been required or a complex Sun search slew strategy is needed. There was also no deep space heritage for the ECASS type sensors nor robustness to loss of a single detector cell. The project consequently decided to use Coarse Sun Sensors.

Many Coarse Sun Sensors to Maximize Sky Coverage

Coarse Sun Sensor configurations with more than eight redundant sensors similar to Reference 8 are not supported without changes to the ACE electronics. A CSS head configuration with greater than eight sensors that would achieve near 4π-steradian “Sun Found” coverage was considered but was rejected due to the associated high cost of the required avionics changes.

CSS Assemblies Mounted on Solar Array Tips

Near 4π-steradian “Sun Found” coverage can theoretically be achieved by mounting CSS pyramids at the tips of the Solar Arrays as described in Reference 9 and others in literature. This concept was immediately ruled out because there are not enough slip rings in the Solar Array Drive Assemblies to support routing the necessary 16 CSS signals.

Digital Sun Sensor

Digital Sun Sensors provide body relative Sun position knowledge with better accuracy than the CSS pyramid assembly. Digital Sun Sensors have a limited Field of View (FOV) in comparison and require a complex Sun Search slew strategy to achieve full Sky coverage. This deficiency, higher cost with respect to the pyramid type assembly, and incompatibility with heritage avionics ruled them out as an option for Psyche.

Sun Search Slew Strategy for Complete Sky Coverage

An initial assessment of the SMAP CSS configuration and similar Sun Search slew strategy for Psyche was performed. It was found that due to a substantial difference in S/C Inertia, it would take Psyche considerably longer to complete the two sets of Sun Search slews to comply with single CSS head failure fault tolerance.

Various slew strategies, such as multiple single axis sequential spacecraft rotations and a spiral search, were analyzed but were unsuccessful in meeting the recovery timeline. Other strategies, such as rotating the solar arrays while monitoring current feedback similar to Reference 10 or a combination of rotating both the solar arrays while slewing the spacecraft were considered but deemed too complex.

A Sun Search slew strategy using a single slew about the minimum principle axis of Inertia (Y-axis) was found to meet the recovery timeline. This slew strategy required the Coarse Sun Sensors to be distributed along the +X face of the spacecraft to sweep out a 4π-steradian “Sun Found” region after slew completion.

CSS Fan Concept

A conventional pyramid of four CSS heads is known to have favorable measurement geometry and a long history of successful use in flight. It is therefore a good conceptual starting point. In principle, enough pyramids could be strung together to form a 4π-steradian Sun-found region. While that might be ideal, it would require a lot of CSS heads and be difficult to lay out on a spacecraft. Alternatively, fewer pyramids could be combined to form a contiguous Sun-found region with an arc length of over 180°. In this configuration, 4π-steradian coverage could be achieved after rotation about a single axis.

Further economy can be achieved by sharing heads between pyramids. Two “outboard” heads of one pyramid can double as two “inboard” heads of an adjacent pyramid. In other words, only two additional CSS heads are needed to add another functional pyramid. Three pyramids could be made with Psyche’s limit of eight heads. In theory, they would be sufficient to form the 180° Sun-found region. However, parts of the Sun-found region would have to use signals lower than what are typically discarded due to the possibility that they could be from the albedo of a nearby body such as Earth. The final configuration presented in the next section deals with this problem by keeping a conventional pyramid in the center of the Sun-found region, then squeezing in the outboard heads so that signals above ~40% can always be used.

FINAL COARSE SUN SENSOR CONFIGURATION

Individual CSSs were configured into prime and redundant strings consisting of eight CSS heads each. The CSSs are grouped into sub-assemblies of two each and are mounted as show in Figure 8. There are two sets of sun sensor assemblies on Psyche – inboard facing (towards +X) assemblies and outboard facing (towards ±Y) assemblies – both of which have unique baffles. Table 1 lists the orientation of the individual CSS head boresights in body coordinates. These orientations lead to a contiguous region of four-head visibility spanning the ½ plane from the -Y to +X to +Y axis. Because the Sun-safe mode will be performed using the low-authority and low-efficiency cold gas system, it was important to orient the CSS fan such that the celestial sphere could be swept out when performing a Y-axis rotation.

Table 1. CSS Head Unit Normal(s)

	S/C body component		
CSS Head ID	X	Y	Z
CSS-1	0.0866993097019315	0.923121405811031	-0.374606593415912
CSS-2	0.0866993097019315	0.923121405811031	0.374606593415912
CSS-3	0.707106781186548	0.5	-0.5
CSS-4	0.707106781186548	0.5	0.5
CSS-5	0.707106781186548	-0.5	-0.5
CSS-6	0.707106781186548	-0.5	0.5
CSS-7	0.0866993097019315	-0.923121405811031	-0.374606593415912
CSS-8	0.0866993097019315	-0.923121405811031	0.374606593415912

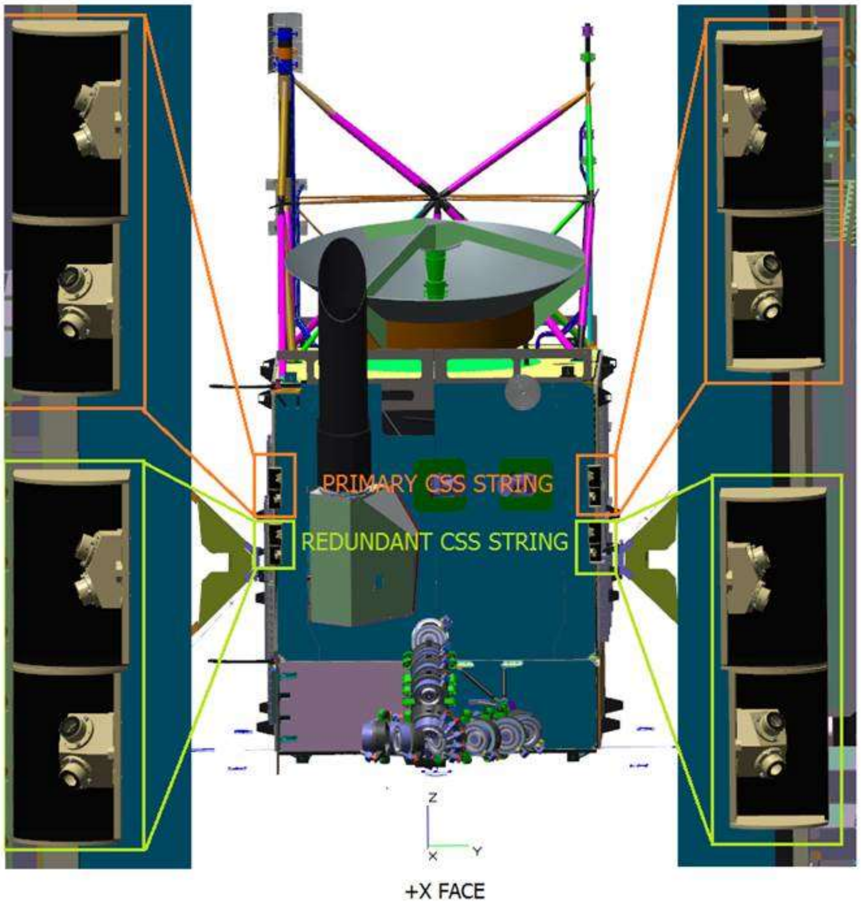

Figure 8. Psyche CSS configuration

Sun Sensor Baffles

A CSS is typically baffled to limit its FOV to avoid effects such as glint, Earth albedo, etc. Baffling is also required to avoid any mechanical intrusions into the sensor FOV from various spacecraft appendages. Figure 9 shows a standard Adcole baffle mounted directly to the sensor.

CSS with Baffle Installed

CSS without Baffle Installed

Figure 9. Model and Image of CSS, with and without baffle installed

For Psyche, the baffles were designed around avoiding glint and intrusions from the solar arrays (deployed along the ±Y axis), SPTs' full range of motion (on the spacecraft +X Face), the DSOC (also on the spacecraft +X Face) and the spacecraft Bus structure itself. This led to Psyche Sun sensors having a different, non-standard baffle design. This included using a combination of individual CSS head baffles along with baffling of the CSS assemblies themselves by using a box-like structure (see Figure 8).

As previously stated, a CSS head contains an internal photovoltaic cell. This cell is of non-zero size and therefore has an aperture. The width of this aperture causes a transient effect as a light source is moved toward and behind a baffle. In short, there exists a region between no light on the cell and full cell illumination where the cell is only partially illuminated. In this transient zone, the electrical output exhibits a sharp decrease from the output at full cell illumination to zero output when the cell is fully shadowed. This transient zone is typically less than 10° when using individual CSS head baffles. Using an extended baffle or external plate not attached to the CSS head further away from the CSS aperture can decrease the transient zone to under 2°. Baffling of the Solar Arrays required a sharp transient zone cut-off and use of unique structural baffling.

Solar Array Deflection

When the Sun-found fan is aligned to allow for a Y-axis spacecraft slew maneuver, Psyche's large solar arrays will intrude into the edge of the fan. An analysis of the maximum deflection of the Psyche solar arrays was performed in an attempt to understand the maximum achievable Sun sensor fan size that avoids viewing the solar arrays when they are in the safe mode orientation (see Figure 10). During nominal operation of Psyche, the solar arrays will frequently intrude into the sensor fields of view. If the spacecraft enters Safe Mode, one of its first actions is to slew the solar arrays to face spacecraft +X, thus orienting the solar arrays out of the sensor fields of view. With the worst-case solar array deflection calculated, the angular size of the Sun sensor FOV fan can be calculated. Various factors, such as array misalignment, tip deflection during external disturbances, thermal distortion, etc. are considered to calculate the total array deflection.

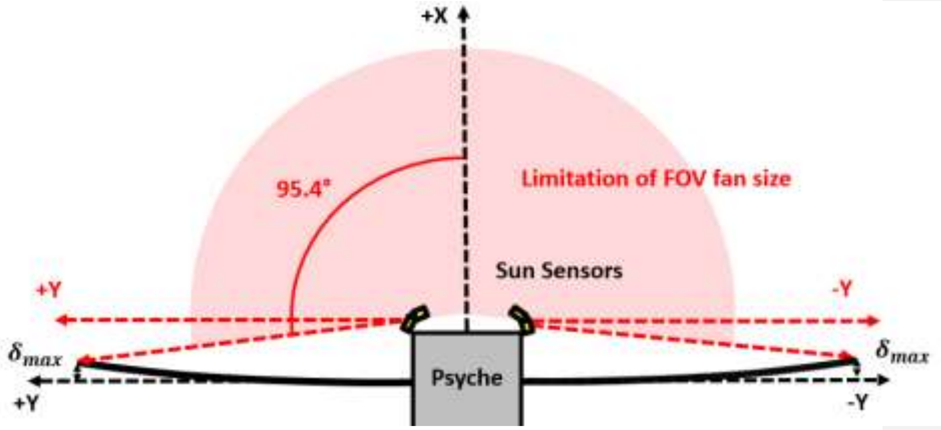

Figure 10. Psyche Sun Sensor FOV Fan

The half-angle fan size of 95.4° represents the maximum fan size that can be achieved without the solar array intruding into the FOV. To determine the design criteria of the Sun sensor baffles, the alignment error of the Sun sensors was subtracted to produce a fan of 94.4°. The minimum fan size is 90°. However, because the requirement must be met with an imperfect rotation about the spacecraft pitch axis, the minimum fan size must be increased to 91°. To avoid glint and other reflections from the solar arrays, the Psyche Sun sensors have baffles in the form of a horizontal plate further away from the photovoltaic cell to sharpen the electrical cutoff and reduce the angular width of the transient zone.

Sun-Found Region

Figure 11 depicts the final Sun-found regions resulting from the head orientations and baffle design previously described. The left side of Figure 11 shows the Sun Found Region in spacecraft body coordinates. The yellow region corresponds to areas with 4 overlapping CSS FOVs. CSS coverage following the Y-axis slew is shown in Figure 12. Full sky coverage with 4 or more CSS heads is achieved with the single rotation.

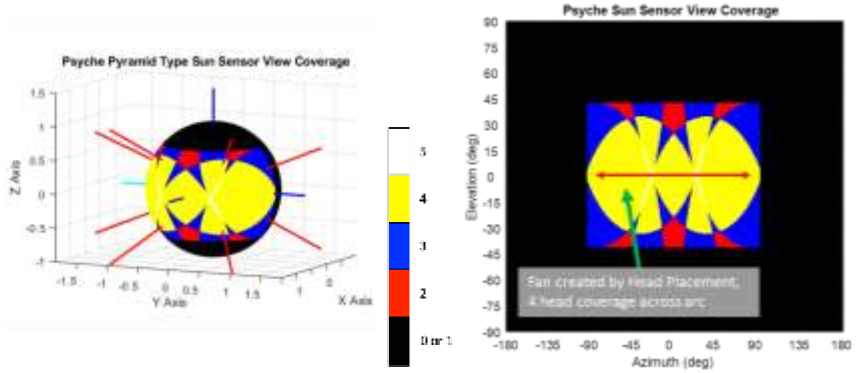

Figure 11. Psyche Sun Sensor FOV Fan

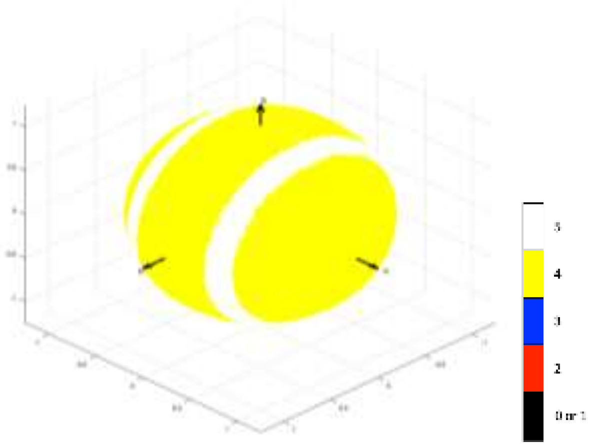

Figure 12. Psyche CSS Coverage post Sun Search Slew (no CSS head failure)

SUN SEARCH ALGORITHM DESCRIPTION

The following is a description of the algorithms used to prove the concept for Sun Search for the Psyche spacecraft.

Control Law Design

The spacecraft's attitude is controlled to follow a sequence of command profiles that allow it to find the Sun, then turn to illuminate the +X face. Algorithms execute with a frequency of 16 Hz, which is about as fast as possible while maintaining robust processor margin on the RAD 750 computer. A proportional-derivative (PD) control law with a fourth-order elliptical low-pass filter provides simple, robust stability margins, including gain stabilization of all flexible-body modes.

Actuation is via reaction wheels or Nitrogen cold-gas thrusters. Since the former have less authority and may be saturated due to a failure event, they are used only in more benign contingency scenarios. Thrusters are the actuators of last resort. Six of them provide three-axis rotational control. Thrust is binary, on or off, with a magnitude of approximately 0.5 N. Pulse width modulation approximates the torque called for by the linear control law. Before application of a minimum and maximum pulse width, duty cycles are the linear-optimal solution for minimum total on time. A minimum pulse width of 16 ms conforms to spacecraft heritage. Given that, a pulse period of 1 s allows for duty cycles low enough to blend with reaction wheel torque when adjusting system momentum. Overheating of the thruster is precluded by enforcing a maximum duty cycle of 80%, or a pulse width of 0.8 s.

Being a control law used during Safe Mode, robustness is heavily favored over performance. Stability margins are correspondingly conservative, leading to a relatively slow control response on the order of a few minutes.

Sun Search Design

Initially, attitude is commanded to propagate about the spacecraft Y axis with a rate of ±0.5°/s. To minimize propellant use, polarity is chosen from the initial rate of the spacecraft. Controlling attitude as well as rate ensures that attitude will not drift enough to miss the Sun if it is near the "keyholes" in the CSS field of view at the spacecraft ±Y axes.

In parallel, the solar arrays are turned to align their normals with the spacecraft's +X axis. This orientation prevents the arrays from interfering with CSS measurements and maximizes power when Sun Acquisition is complete.

Tumbling is nulled and the Sun Search attitude profile is established. Since rotation is about an axis near the minor axis of inertia, the search profile is achieved relatively quickly.

CSS signals are monitored for detection of the Sun. The following approach has proved to be most robust to both nominal and faulty measurement errors:

- Only used are signals greater than what can result from the albedo of nearby bodies such as Earth, Mars, or 16 Psyche.
- As described earlier, the CSS configuration can be thought of as three overlapping pyramids of four heads (see Figure 8). Three or four heads from just one of those pyramids are used. If three heads are sufficiently illuminated in more than one pyramid, the middle pyramid is chosen. This grouping by pyramid has a number of advantages:
    - It avoids using nonsensical, physically impossible combinations of heads.
    - It avoids using combinations of heads on only one side of the "fan" that are nearly coplanar. Doing so would lead to a poor solution for the Sun direction. Instead, as the Sun enters the field of view, it must move more deeply into a well-conditioned region before it can be considered found.
    - It drives towards using the four middle heads, which avoids getting stuck on a poor solution when the Sun is near the edge of the outer heads.
    - It ensures a tractable number of combinations to process.
- For each combination of three heads, the Sun vector is found using each signal as a cosine measurement and linear algebra. If there are four heads, the used combination is the one that results in a Sun vector with a magnitude most different from that from the other three combinations. This criterion discards the head corrupting the Sun vector most.

The Sun is considered found if its direction vector has been determined per the above criteria.

Sun-Relative Attitude Determination

New Sun direction vectors determined from the CSSs are filtered to estimate attitude relative to the Sun. A tapering-gain filter is used. The gain starts at unity to quickly incorporate coarse knowledge of the Sun's direction, then tapers exponentially to a steady-state value that precludes thruster firing in response to CSS signal noise. This implementation has some of the useful characteristics of a Kalman filter but with less complexity and computational overhead.

The estimation routine follows the typical steps. First, attitude its propagated with a gyro-based rate estimate. The result is applied to an inertial Sun direction to find a predicted direction of the Sun in the body frame. The attitude residual is the smallest rotation that aligns the predicted and CSS-based Sun directions. The residual is scaled by the tapered filter gain to compute a correction to the attitude estimate. The estimate is updated by applying the correction to the propagated attitude.

Note that if the estimate of the Sun direction in the inertial frame is valid, the attitude estimate is in fact inertially referenced about two axes, at least to within the accuracy allowed for by the CSS. Attitude about the Sun-direction axis is always entirely undetermined.

Sun Pointing

The attitude command changes from searching for the Sun to aligning it with the spacecraft +X axis after the following conditions are met:

- The spacecraft is detumbled as indicated by sufficiently low attitude rate control errors.
- The Sun is found per the Sun Search algorithm described earlier.

For expedience, the criteria can be reached in parallel. For example, the Sun may be found while detumbling, but is no longer in the CSS field of view when the detumble is complete. But knowledge of the Sun's direction is sufficiently accurate to immediately turn to it and correct lingering error with the additional CSS measurements that follow.

The attitude command is propagated with an angular rate command. It is then corrected to realign spacecraft +X with the Sun direction as determined by the estimate of it in the inertial frame. The correction is large the first time it is applied at the end of Sun Search. Subsequently, it is small, resulting mostly from the motion of the SC-to-Sun direction.

Initially, the rate command is zero and torque resulting from attitude error is limited in magnitude. This configuration effects an attitude slew about a fixed axis with a magnitude in angular rate of approximately 0.1°/s. Once torque no longer exceeds its limit, the attitude slew is deemed nearly complete and the angular rate command is set to a quarter revolution per hour about the spacecraft X axis. After control errors settle, the end state a Safe Mode has been achieved. The spacecraft points its +X axis to the Sun and rotates about the line to ensure that a low-gain antenna will contact Earth.

SIMULATION RESULTS

The following results are with the preliminary algorithms described above. Modeled phenomena include:

- Rigid-body attitude dynamics:
  Included is an initial tumble with a random, normally-distributed angular momentum of 600 N-m-s (3σ), which is on the order of the capacity of all four reaction wheels plus 1°/s about the major axis of inertia.
- External disturbance torque between $\pm 0.25\times 10^{-3}$ N-m per axis
- Thruster torque:
  Pulses are steps with stochastic timing and amplitude errors.
  - Impulse error at minimum on time: ±25%
  - Impulse/thrust error at steady-state: ±5%
- CSS measurement signals
  - Dependence on distance from the Sun
  - Bias and noise of 1.5% of the full signal range:
    The signal-to-noise ratio drops with distance from the Sun.
  - Scale factor error of ±6% due to thermal sensitivity
  - 12-bit quantization
  - One head out
  - Approximation of the baffling described earlier:
    The model includes 10° of transient between all of the Sun being able to illuminate all of the head and none of the Sun being able to illuminate any of the head. When the Sun is in these regions, there is significant potential to spoof the determination algorithms, especially if the baffling is relatively close to the head normal.

The following two figures demonstrate a case when the Sun is initially near the spacecraft +Y axis but just behind the solar array. During the search, the Sun hardly moves in the spacecraft frame. But after about 2½ minutes, it comes around the back of the solar array and enters the outer, transient edge of the CSS field of view. After about three minutes, measurements are sufficient to determine the Sun's direction. Knowledge is immediately corrected, then gradually improves as more measurements are filtered and incorporated. Noise rejection improves as the filter gain tapers, as evidenced by the shrinking red, estimated line with respect to the green, raw-CSS line. After about five minutes, the transient regions are fully cleared.

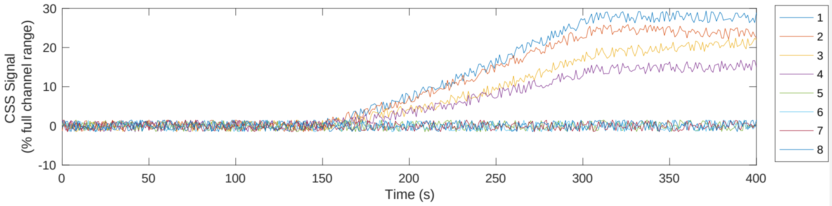

Figure 13. CSS Measurements during "Keyhole" Sun Search.

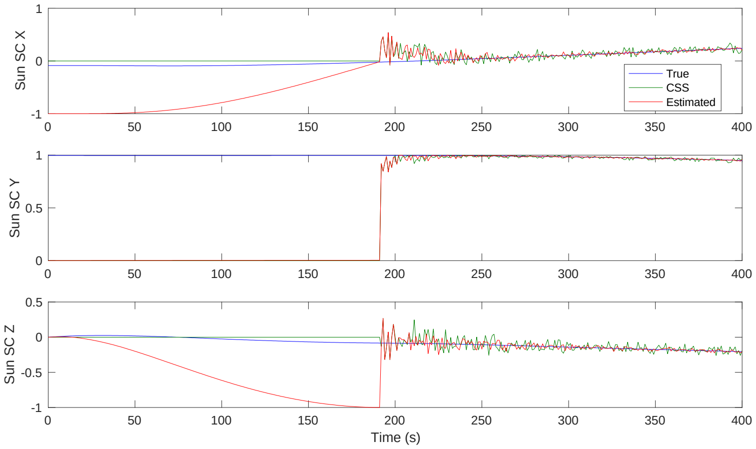

Figure 14. Sun Direction during "Keyhole" Sun Search.

The next figure is from a Monte Carlo of runs. It is the case that took longest to reach the end state of Safe Mode. The initial tumble is extremely fast. After about 15 minutes, the detumble completes and the Sun happens to be nearly 180° from where it needs to be. But the direction of the Sun has already been determined. The spacecraft immediately begins to turn its +X axis to the Sun. After about 40 minutes, attitude transients occur when the estimator updates with new CSS measurements. Within 50 minutes, the end state of Safe Mode is achieved.

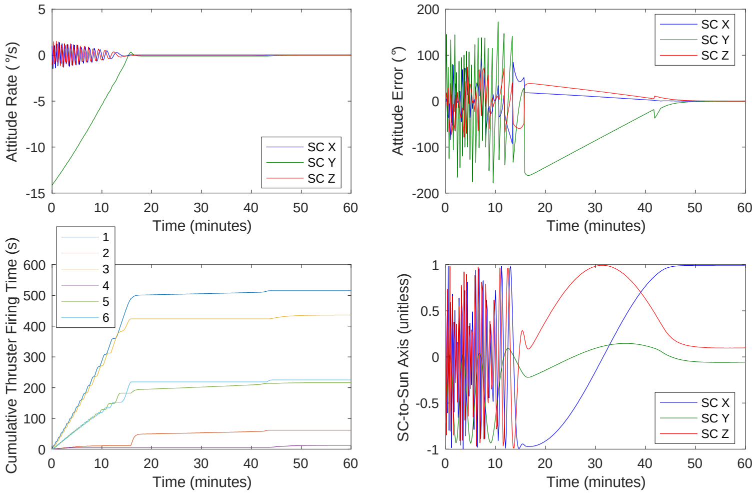

Figure 15. Simulation of Long Sun Acquisition.

The final figure summarizes the statistics from the Monte Carlo. Note that they do not represent actual predicted statistics for the Psyche mission. Rather, they are simply the outcome of a somewhat arbitrary random draw used to explore the problem space.

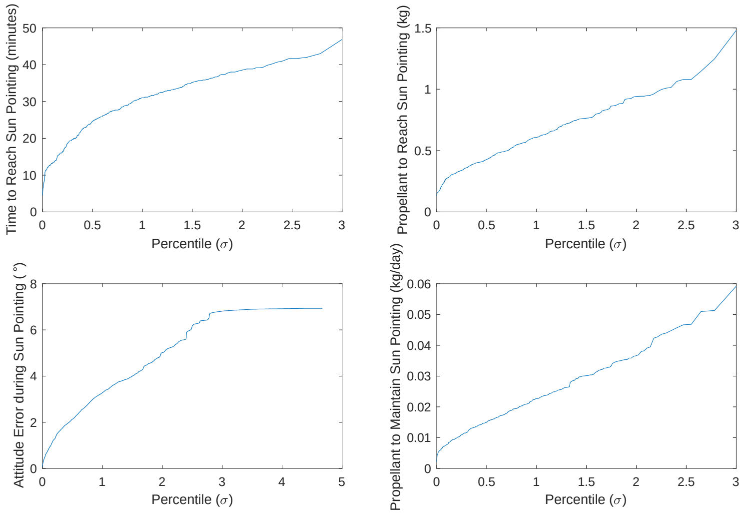

Figure 16. Simulation Monte Carlo Results.

Key takeaways include:

- The achievement of Sun pointing is robust.
- Sun pointing can be reached within the duration required for Safe Mode.
- The propellant required for Safe Mode is within the budget planned for the mission.

Worst-case pointing accuracy is driven by the performance of attitude determination, which can be most affected by large thermal differences between CSS heads.

CONCLUSION AND FUTURE WORK

Various trades were performed as part of the Sun Search Design for Psyche safing. These included looking at heritage Sun Search designs from both Maxar and JPL and selecting hardware compatible with JPL heritage algorithms and available hardware resources. The selected hardware configuration allowed for the creation of a Fan with 4 or more simultaneously illuminated Coarse Sun Sensors on the +X face of the spacecraft. This configuration allowed for a simple Y-axis-slew Sun Search strategy that resulted in full sky coverage. Simulations show that this strategy is robust and meets safing timeline constraints.

The following modifications and enhancements are planned for the final flight algorithms: (1) The control law must be updated based on a more mature and exhaustive set of finite-element models of flexible-body modes. (2) For more robust fault detection, the criteria for deeming that the Sun has been found is to include persistently reasonable and consistent estimator residuals. Sun directions from different combinations of CSS heads may be checked. (3) Attitude slews are to be profiled using heritage algorithms that ramp angular rate based on known capabilities of the spacecraft. Inability to track a profile is used as an indicator for fault detection and isolation.

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