Husky Satellite Lab
University of Washington

HuskySat-2 Mission Design Document

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Abbreviation Table

Abbreviation	Spelled Out Abbreviation	Context
HSL	Husky Satellite Lab	The lab working on the satellite
HS2	HuskySat-2	The current satellite the lab is building for UNP
HS3	HuskySat-3	The future satellite the lab plans to build for a lunar mission
FOUND	Found Open-Source Universal Navigational Determiner	The custom made horizon tracker system
LOST	Lost Open-Source Star Tracker	The custom made star tracker system
DARPA	Defense Advanced Research Projects Agency	The government agency who has set up a plan for lunar satellite infrastructure
NRO	National Reconnaissance Office	The government agency who has set up plans for a robotic autonomous spacecraft
TRL	Technology Readiness Level	A systems engineering term that refers to the level of development and impact of the product
LEO	Low Earth Orbit	The range of orbits the satellite will be deployed in
GNSS	Global Navigation Satellite System	The broader worldwide navigation system
PNT	Position, Navigation, Timing	The system to track the position, navigation, and timing of the satellite
MS	Mission Statement	As defined in UNP user guide
PC	Product Characteristics	As defined in UNP user guide
CD	Customer Drivers	As defined in UNP user guide
MO	Mission Objectives	As defined in UNP user guide
PMO	Primary Mission Objectives	As defined in UNP user guide
SMO	Secondary Mission Objectives	As defined in UNP user guide
SC	Success Criteria	As defined in UNP user guide
MSC	Minimum Success Criteria	As defined in UNP user guide
FSC	Full Success Criteria	As defined in UNP user guide
SOH	State of Health	The overall condition of the satellite’s onboard subsystems
ASTAP	Astrometric Stacking Program	A software product that exists to interpret star tracker data

DQM	Davenport Q-Method	A method that uses a weighted sum of vectors to give an attitude estimate
QUEST	Quaternion Estimator Algorithm	A method that uses an iterative approach to give an attitude estimate
RAAN	Longitude of Ascending Node	One of the six orbital parameters
CI	Continuous Integration	Practice of frequently committing code to a shared repository
PR	Pull Requests	A request to propose and create changes on a shared document
GNU	GNU's Not Unix (recursive)	A free software operating system
API	Application Programming Interface	A set of protocols and tools that allow different software applications to communicate with each other
OpNav	Optical Navigation	A technique used by spacecraft to determine position by taking pictures of celestial bodies with an onboard camera
ADCS	Attitude Determination and Control System	Determines and controls spacecraft attitude
BMS	Battery Management System	Charges and protects the spacecraft battery pack
CCSDS	Consultative Committee for Space Data Systems	Defines the mission telemetry and telecommand framing standards
CDH	Command and Data Handling	Flight computer, storage, state-machine, and subsystem coordination functions
COM	Communications	Space-to-ground command, telemetry, and file-transfer subsystem
EPS	Electrical Power System	Power generation, storage, monitoring, and distribution subsystem
FDIR	Fault Detection Isolation and Recovery	Spacecraft fault response strategy
FEC	Forward Error Correction	Coding overhead applied to the radio link
I2C	Inter-Integrated Circuit	Serial bus used for EPS monitoring and control
IMMU	Inertial and Magnetic Measurement Unit	Combined inertial and magnetic sensor used by ADCS
MTA	Magnetorquer Assembly	Three-axis magnetic actuator assembly
PDS	Power Distribution System	Generates and monitors the regulated spacecraft power rails

PWM	Pulse Width Modulation	Control waveform used for magnetorquers and heaters
RS-485	Recommended Standard 485	Differential serial electrical interface
SDLS	Space Data Link Security	CCSDS link-layer security processing
SPI	Serial Peripheral Interface	Serial bus used for sensor ADC readout
STR	Structures	Primary and secondary spacecraft mechanical structures
THR	Thermal	Temperature sensing and heater-control subsystem
UART	Universal Asynchronous Receiver Transmitter	Asynchronous serial data framing
USB	Universal Serial Bus	Payload camera and storage interface

1.0 - Mission Overview

1.1 - Mission Narrative

Over the past several decades, lunar exploration has become increasingly feasible, with government agencies and commercial organizations developing plans for sustained lunar operations.The NASA Artemis missions, for instance, continue to lay the foundations for a permanent lunar outpost. Similarly, the Defense Advanced Research Projects Agency (DARPA) developed the LunA-10 initiative to accelerate the development of a sustainable and commercially viable lunar infrastructure. As lunar activity expands, reliable navigation will become increasingly important. However, unlike Earth, the Moon lacks a global navigation infrastructure such as the Global Positioning System (GPS), creating a significant challenge for spacecraft operating in lunar and cislunar environments.

A CubeSat-compatible optical navigation system capable of determining a spacecraft’s position and attitude without relying on Earth-based navigation infrastructure would help address this challenge. Such a system could provide a low-cost and adaptable navigation solution for commercial, scientific, and defense missions operating in lunar and deep-space environments. By enabling spacecraft to independently determine their state using observations of celestial bodies and planetary horizons, optical navigation could reduce reliance on external navigation infrastructure, increase spacecraft autonomy, and support future lunar exploration and national security applications.

The Husky Satellite Lab (HSL) aims to contribute to the advancement of autonomous lunar and deep-space navigation by developing a fully autonomous position and attitude determination system capable of operating without external navigation infrastructure. HSL seeks to provide a lower-cost alternative to existing commercial off-the-shelf navigation systems while maintaining comprehensive documentation and an open-source development approach. By reducing reliance on external navigation infrastructure, this technology could provide greater operational autonomy and resilience for commercial, scientific, and defense missions. HSL's goal is to demonstrate that these capabilities can be developed at the CubeSat scale, lowering barriers to future lunar exploration and enabling more accessible and autonomous spacecraft for both civilian and national security applications.

The HuskySat-2 (HS-2) mission will address two key components of the optical navigation problem: star-based attitude determination and planetary-limb-based position determination. HSL has developed two open-source payloads, LOST (Lost Open-Source Star Tracking) and FOUND (Found Open-source Universal Navigation Determiner), to demonstrate these capabilities. LOST uses observations of stars to determine the spacecraft's attitude, while FOUND uses observations of a planetary horizon to determine the spacecraft's position. Together, these systems are intended to demonstrate an autonomous navigation capability that can operate independently of GPS and other external navigation infrastructure. This capability has applications beyond scientific exploration, as GPS-independent navigation can provide

increased resilience and autonomy for spacecraft supporting commercial, scientific, and defense missions.

LOST (Lost Open-Source Star Tracking) is an in-house developed star-tracking software that determines spacecraft attitude from images of the surrounding star field. Following image capture, LOST processes the image through three primary stages: centroid detection, star identification, and attitude estimation. During centroid detection, LOST identifies the centers of visible stars to sub-pixel accuracy. The detected stars are then matched to a database by comparing the geometric patterns observed in the image with known star patterns. Once the stars are identified, LOST determines the spacecraft rotation that best aligns the observed and known star directions and outputs an attitude estimate. LOST can operate in both lost-in-space and tracking modes, allowing it to determine attitude without prior knowledge or efficiently update an existing attitude estimate when operating continuously. Its low computational demands and reduced cost make LOST a promising alternative to conventional star trackers. The LOST algorithm was presented at the 2023 Small Satellite Conference and has since received significant interest through its publicly available paper and open-source implementation [8].

FOUND (Found Open-source Universal Navigation Determiner) is an in-house developed optical navigation method that determines a spacecraft's position relative to a celestial body using images collected by a wide-field-of-view navigation camera. During operation, FOUND captures an image of the target body and uses Zernike moments to detect the illuminated limb, or edge, of the Earth. Using the known size and shape of the Earth and the apparent geometry of the detected limb, FOUND determines the vector from the spacecraft to the center of the Earth. This vector is then combined with the spacecraft attitude determined by LOST to calculate the spacecraft's position in global equatorial coordinates. Unlike feature-tracking navigation methods, FOUND does not rely on matching surface features to a stored database, reducing computational requirements and avoiding dependence on potentially incomplete or lower-quality surface maps, particularly for the Moon and other celestial bodies. By focusing on horizon/limb detection rather than feature tracking, FOUND also provides a clear distinction between optical position determination and attitude-determination techniques that are often conflated. Additionally, FOUND is designed to operate using both visible and infrared imagery, potentially reducing the need for specialized infrared sensors while maintaining robust limb detection in the presence of image noise.

Together LOST and FOUND provide GPS-denied and deep space navigation, improving upon expensive COTS attitude systems ($30k-$50k for star trackers with 7-30 arcsec accuracy [9]) and pioneering position determination. HS-2 validates LOST and FOUND in LEO with a GNSS and commercial star tracker as a ground truth for comparison. This technology will pave the way for future lunar missions like HS-3 which will need reliable navigation.

1.2 - Military Relevance

The space domain has become increasingly contested, increasing concerns regarding the reliability and availability of Global Positioning System (GPS)-based Position, Navigation, and Timing (PNT). GPS signals can be degraded or disrupted by jamming, spoofing, system failures, or other adversarial actions, creating a need for navigation capabilities that do not depend solely on GPS. The development of GPS-independent navigation systems is therefore relevant to both national security and future space exploration, particularly as spacecraft operate farther from Earth and beyond the coverage of existing navigation infrastructure.

One approach to GPS-independent navigation is optical navigation (OpNav), in which spacecraft use onboard cameras to extract navigation information from observations of celestial objects and planetary bodies. Because optical navigation relies on passive measurements collected onboard, it can provide an independent source of navigation information without requiring continuous access to external navigation infrastructure. HuskySat-2 investigates two complementary OpNav techniques: LOST, which uses observations of stars to determine spacecraft attitude, and FOUND, which uses observations of Earth's planetary limb to determine spacecraft position. Together, these systems provide a path toward autonomous position and attitude determination in environments where conventional navigation sources may be degraded or unavailable.

GPS-Denied Operations

One of the most significant applications for GPS-independent navigation is operation in GPS-denied environments. GPS signals may be unavailable or compromised due to jamming, spoofing, loss of signal, or disruptions to supporting infrastructure. The Air Force's Technology Horizons report identified space resiliency, particularly in precision navigation and timing when GPS is degraded, as an important future capability. The report also highlighted autonomous systems and their use in GPS-denied environments as significant areas of Air Force development. An independent optical navigation capability can provide an additional source of PNT during these conditions, reducing reliance on GPS as a single source of navigation information and increasing spacecraft resilience.

FOUND is particularly relevant as a fallback and independent navigation capability. It is not intended to replace GPS or other established navigation systems when they are available. Instead, FOUND can provide an independent position measurement that can complement conventional navigation systems and help identify discrepancies in the GNSS solution, including potential spoofing or other navigation anomalies. When GNSS is degraded, unavailable, or determined to be unreliable, FOUND can provide an alternative source of position information to maintain navigation capability. This redundancy can reduce reliance on a single navigation source and support continued spacecraft operations during contested or disrupted conditions.

Autonomous Operations

Increasing spacecraft autonomy is another major area of interest for defense and space operations. Autonomous spacecraft can reduce dependence on continuous human intervention and external infrastructure while increasing operational flexibility. Organizations such as the Defense Advanced Research Projects Agency (DARPA) and the National Reconnaissance Office (NRO) have demonstrated interest in developing increasingly autonomous and resilient space systems. DARPA's Assured Autonomy program states that autonomous systems are increasingly critical to current and future Department of Defense mission needs.

A self-contained optical navigation system can contribute to this autonomy by allowing a spacecraft to determine aspects of its own state using onboard measurements and processing. LOST and FOUND can provide attitude and position information without requiring a navigation solution to be continuously supplied from the ground. This capability could allow spacecraft to continue making navigation decisions through periods of limited communication or ground contact and could support future autonomous spacecraft operations.

Space Operations

Reduced dependence on external navigation infrastructure can also provide operational benefits for spacecraft. Conventional orbit determination may depend on ground tracking, communication windows, or externally supplied orbital information. A spacecraft equipped with an onboard optical navigation capability can instead make its own navigation measurements, allowing it to continue estimating its state during communication outages or limited ground-contact opportunities.

This capability is particularly relevant for CubeSat-class spacecraft, which may have limited communications, computational, and power resources compared with larger spacecraft. A relatively low-cost, onboard optical navigation system could provide an additional layer of navigation resilience without requiring the spacecraft to rely entirely on continuous ground support.

Deep-Space and Cislunar Navigation

The need for GPS-independent navigation becomes even more significant beyond Earth orbit, where terrestrial GNSS infrastructure is unavailable. Future cislunar and deep-space spacecraft will require alternative methods for determining their position and attitude without relying exclusively on Earth-based navigation services. Optical navigation provides a potential solution by using observations of stars and planetary bodies that are available throughout much of the spacecraft's trajectory.

This capability could support future missions operating around the Moon and other celestial bodies. For example, initiatives such as DARPA's LunA-10 seek to accelerate the development of lunar infrastructure, creating a potential need for autonomous navigation capabilities that can operate before a dedicated lunar PNT infrastructure exists. The ability to determine spacecraft state using onboard optical observations could therefore increase the autonomy and resilience of future lunar CubeSat networks and other spacecraft operating in cislunar space. Autonomous navigation can also reduce reliance on ground-based tracking and navigation support, decreasing the amount of deep-space communications capacity required for routine operations. This could help alleviate constraints on increasingly capacity-limited deep-space communication networks and allow available communications time to be prioritized for mission-critical data and commanding.

FOUND as a Complement to Ground-Supplied Orbital Predictions

FOUND can also provide a complementary navigation measurement to ground-supplied orbital predictions, such as those generated using Two-Line Element (TLE) data. TLE-based methods provide an estimate of a spacecraft's future position by propagating a previously determined orbital state. As the orbit is propagated without new observations, uncertainties in the initial state and orbital model can contribute to increasing prediction error. One study found that, over a three-day propagation period, TLE predictions had average errors of approximately 21 km, with some objects exceeding 100 km of position error.

Unlike a propagated orbital prediction, FOUND is designed to make a new optical measurement of the spacecraft's position relative to a planetary body. This provides an opportunity to generate a new navigation measurement rather than relying solely on the continued propagation of a previous orbital state. In the event of an unexpected maneuver or an extended period without updated ground-derived orbital information, an independent optical measurement could help re-estimate the spacecraft's position and constrain navigation error.

Complementary Navigation and Resilience

FOUND is therefore not intended to replace GPS, ground-based tracking, inertial navigation systems, or other established navigation technologies. Instead, its value comes from providing an independent source of navigation information that can be incorporated into a sensor-fusion architecture alongside these existing systems. GNSS provides highly accurate navigation when its signals are available, ground-based tracking provides high-quality externally determined orbital information, and inertial systems provide continuous state propagation. Each system, however, has limitations: GNSS is vulnerable to signal disruption and spoofing and is unavailable beyond its coverage, ground-based tracking depends on external infrastructure and

communications opportunities, and inertial navigation errors accumulate over time due to sensor drift. By providing an independent optical position measurement, FOUND can help identify discrepancies between navigation sources, support continued navigation when individual systems become unavailable or unreliable, and improve the overall resilience of the spacecraft's navigation solution.

By providing an independent optical measurement, FOUND could help mitigate these limitations when used alongside conventional navigation systems. The combination of multiple navigation sources can reduce reliance on any single system and provide a fallback when one source becomes unavailable. This approach is particularly valuable for spacecraft operating in GPS-denied, contested, cislunar, and deep-space environments.

To contribute to these areas of military relevance, HuskySat-2 will characterize the performance of an in-house, CubeSat-compatible, and open-source optical navigation system. The mission will establish flight heritage for LOST and FOUND while generating performance data that can guide their continued development. The resulting technology can provide a lower-cost and accessible approach to autonomous optical navigation while reducing the operational risks associated with dependence on a single navigation source. Future missions, including HuskySat-3, can build upon the results of HS-2 to extend these capabilities toward lunar navigation. In this way, HS-2 contributes to the development of resilient, autonomous navigation capabilities for future CubeSat, cislunar, and deep-space missions.

Comparison of LOST/FOUND to Other Navigation Systems

Navigation Method	**Primary Limitation**	**How LOST and FOUND Complement It**
GNSS	Limited coverage; vulnerable to jamming, spoofing, and signal loss.	Provides navigation independent of GNSS.
Ground-based tracking	Requires ground infrastructure and communication windows.	Enables onboard navigation with less ground dependence.
Inertial Navigation System (INS)	Position error accumulates due to sensor drift.	Provides independent measurements to constrain drift.
Ground-supplied TLE	Prediction uncertainty increases with propagation time.	FOUND provides new onboard position measurements.
Conventional star tracker	Primarily provides attitude, not position.	LOST provides attitude while FOUND provides position.
Terrain-relative navigation	Requires identifiable and resolvable surface features.	FOUND uses the planetary limb instead of surface features.

LOST + FOUND	Dependent on suitable optical observations.	Provides independent optical position and attitude determination.

1.3 - Customer Definition

The primary stakeholders for HuskySat-2 are the LOST and FOUND teams, which are focused on advancing the technology toward Technology Readiness Level (TRL) 7 through on-orbit validation for future lunar missions, including HuskySat-3. Beyond these internal stakeholders, the potential applications of LOST and FOUND can be divided into two primary customer groups: commercial and defense customers seeking autonomous navigation capabilities for operational missions, and scientific customers seeking accessible technology for future research and exploration missions.

1.3.1- Commercial/Defense Customer

Potential commercial and defense customers include organizations developing lunar infrastructure, autonomous spacecraft, and missions operating in GPS-denied or contested environments. Examples include organizations supporting initiatives such as DARPA's LunA-10, the National Reconnaissance Office (NRO), and commercial lunar mission operators. These customers could use LOST and FOUND to provide autonomous position and attitude determination when conventional navigation infrastructure is unavailable, unreliable, or undesirable. This capability is particularly valuable for spacecraft operating beyond the coverage of GNSS or in environments where communication with Earth may be limited.

For these customers, key considerations include navigation accuracy, reliability, cost, size, weight, power consumption, computational requirements, and technology maturity. LOST is intended to provide a high-performance, low-cost alternative to conventional commercial star trackers, while FOUND provides position determination using planetary-limb observations rather than relying on GNSS. Together, the systems provide a path toward autonomous position, navigation, and timing (PNT) capabilities for CubeSat-class spacecraft. Key performance targets include a 95% star identification rate for LOST and approximately 15 km position accuracy for FOUND.

Cost-effectiveness and risk reduction are particularly important for customers considering the integration of a new navigation technology into a spacecraft. Cost-effectiveness is evaluated by comparing the performance and mission benefits of LOST and FOUND against the financial, physical, computational, and operational costs of existing solutions. Risk reduction is achieved through progressive technology development, including analytical proof-of-concept, component- and assembly-level verification, software and hardware testing, and ultimately flight heritage.

Demonstrating the technology in orbit provides evidence that the system can operate in the space environment and reduces uncertainty associated with its integration into future missions.

HuskySat-2 serves as the on-orbit validation mission for LOST and FOUND. By demonstrating the technology in LEO, HS-2 will generate flight data that can be used to characterize the performance, limitations, and reliability of both payloads. The mission will establish flight heritage and provide quantitative measurements of navigation performance against established reference systems. Successful demonstration of the technology will increase the TRL of LOST and FOUND and provide future commercial and defense users with greater confidence in their ability to support autonomous operations in lunar, deep-space, and other GPS-denied environments.

1.3.2 - Scientific Customer

Scientific customers include future HSL missions, such as HuskySat-3, as well as university-led and other scientific CubeSat missions that could use LOST and FOUND as an accessible platform for autonomous navigation research. These customers are interested not only in navigation performance, but also in the ability to understand, reproduce, modify, and build upon the technology. For future lunar missions such as HS-3, HS-2 provides an intermediate step between development in a laboratory environment and operation in a cislunar or lunar environment.

Scientific missions require accurate, GPS-independent PNT capabilities to support spacecraft operations and generate reliable scientific data. LOST and FOUND provide complementary navigation measurements, with LOST determining spacecraft attitude from stellar observations and FOUND determining spacecraft position relative to a planetary body. Together, these capabilities can provide a foundation for autonomous navigation in environments where GNSS is unavailable. Demonstrating these capabilities in LEO allows HSL to characterize their performance before applying them to the more challenging conditions expected during future lunar missions.

In addition to performance, accessibility and ease of integration are important considerations for scientific customers. An open-source development approach, comprehensive documentation, standardized interfaces, and the use of readily available components can reduce barriers to adoption and allow future researchers and mission developers to adapt the technology to their specific missions. Detailed documentation of the design, testing, and performance of LOST and FOUND also supports reproducibility and allows future teams to identify limitations and continue improving the system.

HuskySat-2 will support these scientific applications by providing on-orbit performance data, documented development processes, and demonstrated flight heritage for LOST and FOUND. The results of HS-2 will establish a performance baseline that can be used to guide future development and determine which aspects of the system require additional refinement before lunar deployment. In particular, HS-2 will provide the data and experience necessary for future

missions such as HS-3 to extend the technology from LEO demonstrations toward cislunar and lunar navigation.

Ultimately, the scientific value of LOST and FOUND extends beyond their use on a single HSL mission. By developing the systems as relatively low-cost and open-source technologies, HSL can provide future university and scientific missions with an alternative to expensive proprietary navigation solutions. The combination of demonstrated flight heritage, documented performance, and accessible design will allow future missions to use HS-2 as a foundation for continued research into autonomous optical navigation.

1.4 - Mission Statement and Objectives

HuskySat-2 Mission Statement:

Measure the capabilities of LOST and FOUND as a GPS-independent optical navigation solution for cubesat applications.

Table 1: *Mission Objectives*

ID	Mission Objective
MO-1	HS2 will report spread and bias for LOST
MO-2	HS2 will report spread and bias for FOUND
MO-3	Determine the precision of attitude measurements from LOST
MO-4	Determine the precision of position measurements from FOUND.
MO-5	Downlink images taken for LOST and FOUND

Table 2: *Mission Success Criteria*

ID	Criteria
MSC-1	Determine with 99% power and 1% error rate if FOUND calculates Earth's lit limb to be within the mesosphere 3-sigma.
MSC-2	Determine with 99% power and 1% error rate if LOST calculates attitude of the satellite to within 30 [TBR] arcseconds 3-sigma across-boresight.
MSC-3	Determine with 99% power and 1% error rate if LOST calculates attitude of the satellite to within 30 [TBR] arcseconds 3-sigma around-boresight.
MSC-4	Downlink 1 image of the stars and 1 image of Earth's lit limb.
FSC-1	Determine with 99% power and 1% error rate if FOUND calculates the satellites position within TBD meters 3-sigma
FSC-2	Determine with 99% power and 1% error rate if LOST calculates attitude of the satellite to within 9 [TBC] arcseconds 3-sigma across-boresight.
FSC-3	Determine with 99% power and 1% error rate if LOST calculates attitude of the satellite to within 45-50 [TBC] arcseconds 3-sigma around-boresight.
FSC-4	Downlink and deliver [TBD] images for LOST and [TBD] images for FOUND.
FSC-5	HS2 will report spread and bias for LOST and FOUND

2.0 - Science Overview

Optical navigation (OpNav) is a method of determining a spacecraft's position and attitude using observations of objects within its environment. Unlike traditional navigation methods such as Global Navigation Satellite Systems (GNSS), which rely on external infrastructure, optical navigation uses measurements collected by onboard cameras. This allows a spacecraft to estimate its state independently of Earth-based navigation systems, making OpNav particularly valuable for operations in GNSS-denied environments, cislunar space, and deep space. The use of passive optical sensors also provides a relatively low-power approach to autonomous navigation, supporting applications across scientific, commercial, and defense missions.

The fundamental principle of optical navigation is to extract measurable features from an image and relate those observations to known physical properties or reference data. Different objects and features provide different types of navigation information. Distant objects such as stars appear as point features within an image and can be used to determine spacecraft attitude. When a celestial body is close enough for its shape to be resolved but individual surface features cannot be distinguished, its apparent limb, or visible edge, can be used to determine the spacecraft's position relative to the body. If identifiable surface features such as craters, mountains, or coastlines can be resolved, those features can be matched to known maps or reference imagery to provide position information. Finally, illumination features, such as the direction of shadows or the illuminated portion of a celestial body, can provide information about the direction and geometry of the Sun relative to the spacecraft.

Each type of optical measurement has advantages and limitations. Terrain-based navigation can provide highly accurate position estimates when recognizable surface features can be resolved. However, the effectiveness of this approach decreases as the spacecraft moves farther from the target body, where surface features may no longer be distinguishable. Temporary features such as clouds can also obscure otherwise useful landmarks. Planetary-limb navigation provides an alternative because it does not require individual surface features to be resolved. Instead, the apparent size and shape of a celestial body's limb can be related to the spacecraft's distance from that body. This allows optical navigation to remain viable over a wider range of distances and environmental conditions.

The accuracy and availability of optical navigation also depend on factors such as camera resolution, field of view, exposure time, lighting conditions, and spacecraft attitude. For example, long exposure times can introduce image blur, while poor illumination can make individual features difficult to detect. These limitations motivate the use of complementary optical navigation techniques rather than relying on a single observable.

HuskySat-2 demonstrates two complementary forms of optical navigation by focusing on star and planetary-limb observations. LOST uses stars as point features to determine spacecraft attitude, while FOUND uses Earth's illuminated limb to determine spacecraft position. Together, these techniques demonstrate how different optical observations can be combined to provide

autonomous spacecraft state determination without relying on GNSS or other external navigation infrastructure.

2.1 - LOST (Star Tracker)

2.1.1 - Introduction to Star Trackers

Star trackers are the most commonly used method of attitude determination in space. Their popularity stems from the high accuracy they are able to achieve compared to other systems, such as sun trackers and magnetometers.

2.1.2 - Motivation for LOST

LOST is an important milestone in Husky Satellite Lab's ambitious project of "solving" the space optical navigation problem. It is the only implementation of a low compute open source star tracker. This makes LOST only as expensive as the camera you pair with it.

Table 3: *Star Tracker State-of-the-Art*

Specifications	**Example, Proprietary**	**Example, Open-Source**	**Example, Open-Source**
Model	Sagitta Star Tracker	Tetra3	SOST
Manufacturer	ArcSec	European Space Agency (ESA)	Space and Planetary Exploration Laboratory
Cost, $	35,000 - 45,000	Free	Free
Compute Load	Undisclosed. Nominal power consumption of 1.5W	Very large database (up to 5GiB). Usage of heavy third-party libraries like numpy and scipy	Usage of slower third-party software Source Extractor and Match. Average power consumption of 1.0W when running star tracker
Accuracy Cross-boresight (Arcsec 1σ)	2	10	36
Accuracy Around Boresight (Arcesc 1σ)	10		108
Documentation	https://www.arcsec.sp	https://tetra3.readthe	https://ieeexplore.iee

	ace/pdf/Sagitta%20Star%20tracker%20datasheet%20V2.1.pdf	docs.io/en/latest/	e.org/document/9179736

2.1.3 - LOST Pipeline

LOST processes via centroiding, star identification, and attitude estimation.

1. Centroiding: Center of gravity for star detection
2. Star Identification: Tetra (hash tables for patterns) vs Pyramid (triangle matching) algorithms
    a. Tetra: 95% accuracy, 20ms
    b. Pyramid: 92% accuracy, 15ms
    c. Attitude determination: DQM/QUEST for quaternions

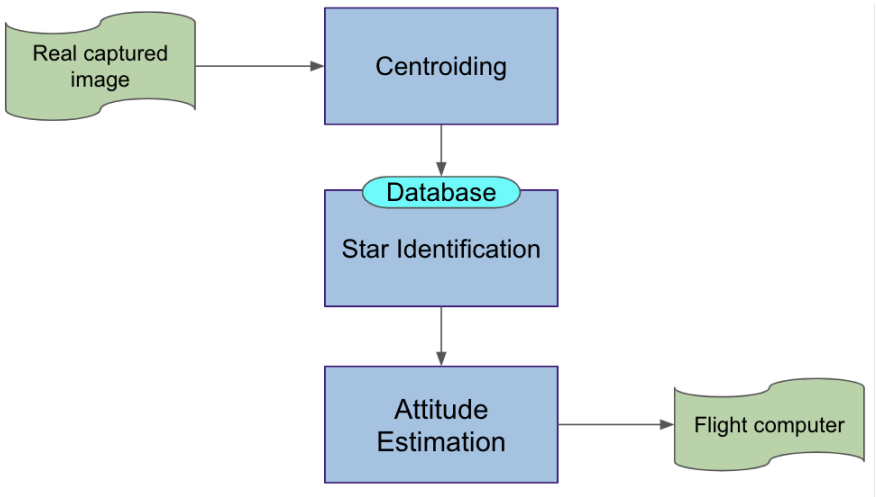


Figure 1: LOST Pipeline

On HS-2, this pipeline will run on a Beaglebone Black computer, interfacing with ADCS for navigation. The University of Washington's HS-2 mission seeks to validate LOST software through implementing through the following steps all while supporting precise pointing:

1. Use a camera to capture star fields
2. Process pictures onboard using LOST
3. Output quaternions of attitude determination results

Centroiding

Inputs: Grayscaled pictures
Outputs: A collection of pixel coordinates (x_c, y_c), where each set of coordinates is a centroid, or star center
Algorithm: Center of gravity

1. Identify every cluster of pixels with brightness over a certain threshold $\mu + \alpha\sigma$, where μ

is the mean pixel brightness, σ is the standard deviation, and α is an empirically tuned constant. Each cluster represents a possible star.

2. Mitigate the effect of background noise by subtracting the mean pixel brightness μ.
3. Compute the coordinates of the centroid:

$$(x_c, y_c) = \frac{1}{\sum_{(x,y,w)\in B} w} \cdot \sum_{(x,y,w)\in B} [w \cdot (x, y)]$$

Equation 1. Center of Gravity

Each pixel has coordinates $(x,\ y)$ and brightness w.

Center of gravity is simple but reliable. The accuracy gained from more complex algorithms like iterative weighted Center of gravity and Gaussian least squares fit is insignificant and not worth the loss in efficiency.

Star Identification

LOST implements both the Tetra and Pyramid star identification algorithms. For HS-2, the final algorithm is dependent on further testing in camera-specific conditions, noise tolerance, and real-world images.

Table 4: *LOST Star Identification*

	Tetra	**Pyramid**
Description/Function	Matches identified centroids with stars from star catalog	
Input	A list of centroids, algorithm-specific star database, list of stars in database, a star catalog (Yale's Bright Star Catalog).	
Output	A list of star identifier objects that represent centroids identified in the star catalog.	
Pseudocode (simplified)	1. Select the 4 brightest stars. 2. Compute and normalize 6 pairwise distances. 3. Sort the distances and generate a hash. 4. Look up the hash in a catalog to find a match. 5. If there is no match, try a different set of 4 stars.	1. Select 4 stars with the shortest total inter-star distances. 2. Use the database to find catalog star pairs matching key distances. 3. Build hash tables for quick lookups. 4. Check if all distances match a catalog pattern. 5. If a unique match exists, return it; otherwise, try new

		stars.
Advantages	• Tetra is a very fast algorithm. It has the benefit of fast lookup times because it constructs a special hash table. • High availability even with more false stars.	• The Pyramid algorithm has a low false-positive rate because matching 4-star patterns is unlikely to result in false star identification. • High availability even with high centroid error.
Disadvantages	• Tetra's hash table requires a large amount of memory to maintain a reasonable load factor. • Availability decreases significantly with high centroid error.	• Slower than our Tetra implementation. • Availability decreases when given more false stars.

Attitude Estimation

Attitude estimation algorithms find a rotation that brings the star vectors in the reference frame as close as possible to the observed star vectors by minimizing Wahba's loss function:

$$L(\mathbf{A}) = \frac{1}{2}\sum_{i=1}^{N} w_i |u_i - \mathbf{A}v_i|^2$$

Eq. 2 Wahba's Loss Function

Table 5: *LOST Attitude Estimation*

	TRIAD (Triaxial Attitude Determination)	**DQM (Davenport Q-Method)**	**QUEST (Quaternion Estimator Algorithm)**
Description/Function	TRIAD is a basic approach to attitude determination, using exactly two reference vectors to directly calculate a direction cosine matrix.	The Davenport Q-Method formulates the attitude estimation problem as an eigenvalue problem by maximizing a weighted sum of vector alignments	QUEST uses an iterative Newton-Raphson approach to solve for the optimal quaternion.

		using quaternions.	
Input	A list of star identifiers given by the star-identification algorithm.		
Output	Euler angles representing attitude (right ascension, declination, roll). Can be converted to quaternion.		
Mathematics	• Selects two input vectors from observations. • Builds two orthonormal triads from the two vectors. • Returns the product of one triad (the photo frame) with the transpose of the other triad (the catalog frame).	• Forms a K-matrix from weighted observations. • The optimal quaternion corresponds to the eigenvector of the largest eigenvalue of this matrix. • Requires solving a 4×4 eigenvalue problem.	• Also constructs the K-matrix, but instead of solving the full eigenvalue problem, it uses an iterative approach to find the largest eigenvalue. • Uses the Newton-Raphson method to refine the solution.
Computational Complexity	Very low. Does not perform eigenvalue decomposition or iterative optimization like the other two methods.	Moderate. It requires solving an eigenvalue problem, which can be computationally expensive in real-time applications.	Lower than DQM since it avoids full eigenvalue decomposition.
Accuracy	Less accurate if there are more than two vector observations, because only two are used.	Very high due to its deterministic nature.	Nearly as accurate as DQM but slightly less optimal due to approximations.
Advantages	• Fast and computationally efficient. • Deterministic.	• Provides a closed-form optimal solution. • Resistant to measurement noise.	• Computationally efficient. • Well-suited for real-time applications.
Disadvantages	• Can only use exactly two	• Solving an eigenvalue	• Requires an initial estimate

	vector inputs. ● Sensitive to noise. ● Accuracy varies based on which star is selected as primary during triad construction.	problem can be computationally expensive. ● Less efficient for real-time applications compared to QUEST.	for iteration. ● May require more iterations to converge for some cases.

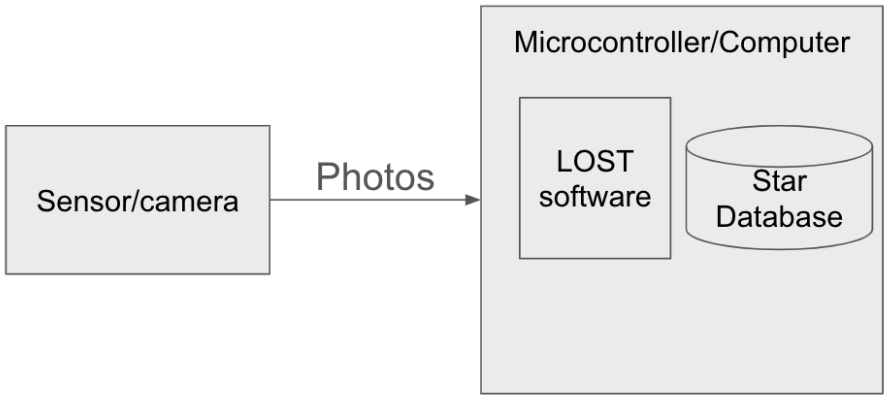


Fig 2. Sensor to Computer Diagram

LOST will use a camera (XIMEA xiQ-S7) to capture star pictures and run the LOST software on the CDH computer (BeagleBone Black Industrial).

In scenarios representative of a low-cost star tracker, LOST correctly identifies over 95% of images while completing the full star-tracking pipeline in less than 35 milliseconds on a Raspberry Pi and using less than 1 MiB of memory with a database smaller than 350 KiB [8]. These computational and memory requirements indicate that LOST can be implemented on resource-constrained hardware. The LOST study estimates that on a computer with similar processing power (within an order of magnitude) such as the BeagleBone Black Industrial, the processing time would increase by at worst an order of magnitude, resulting in an estimated processing time of less than 0.5 seconds under typical conditions. In high-noise conditions, processing could take approximately 1 second, while memory usage would remain below 1 MiB [8] satisfying the need for a low-compute star tracker.

2.2 - FOUND (Horizon Tracker)

2.2.1 - Intro to Horizon Trackers

Earth provides a major reference point in space, occupying a significant portion of the sphere of visibility in low Earth orbit (LEO). Horizon trackers take advantage of this by taking images of Earth's edge and solving for attitude and altitude given planetary radii and an attitude, often from a star tracker. Longitude can be solved for given date/time data. Horizon tracking has historically been used by NASA missions to navigate based on atmosphereless bodies, with Viking demonstrating 2km accuracy on Deimos, and Voyager utilizing horizon tracking to satisfy navigation accuracy requirements that radiometric data could not achieve at large distances.

2.2.2 - Motivation for FOUND

The primary motivation for FOUND lies in autonomy and redundancy for missions where GPS signals are unavailable, unreliable, or intentionally denied. While GPS remains the gold standard for Earth-orbiting satellites, CubeSats operating beyond low Earth orbit (e.g., lunar or deep-space missions) or in contested environments (e.g., military scenarios) cannot rely on GPS constellations. FOUND enables autonomy in GPS-denied scenarios, targeting 10 km position accuracy for CubeSat missions around Earth, with low compute processing to fit the rigid power and thermal constraint imposed on CubeSats. 2km position accuracy can be achieved for atmosphereless bodies, such as the moon.

FOUND provides a self-contained solution that leverages celestial bodies for altitude determination. Though less precise than GPS in ideal conditions, FOUND hopes to achieve sufficient accuracy for many CubeSat applications while avoiding single-point failures. Additionally, advancements in edge computing enable lightweight processing of optical data, mitigating power trade-offs. This makes FOUND a primary or backup solution for missions prioritizing survivability, sovereignty, or extraterrestrial exploration.

2.2.3 - FOUND pipeline

FOUND performs edge detection on an image of Earth's horizon, and stores a list of edge points. It then takes in attitude information from either LOST (Experiment C) or a truth measure (Experiment B), and uses Earth's radii as parameters to transform the edge points into a vector space where Earth is represented by a unit sphere. From here, the transformed edge points can be inputted to a regression algorithm solving for the sphere's location relative to the camera. This is used to determine the satellite's position as a vector in the transformed space, which is ultimately transformed back into regular space which can be used to derive orbital elements independent of Earth's rotation. The algorithm can be adapted to any celestial body by specifying object radii and rotation axes.

FOUND consists of a suite of algorithms to assist with position determination and operates as a modular set of static binaries.

The satellite takes in ground commands to determine which atomic algorithms to perform experiments on, and selects the proper binaries. The science logic layer grabs the input and data and runs the algorithms via a modular assembly procedure, outputting data and logs.

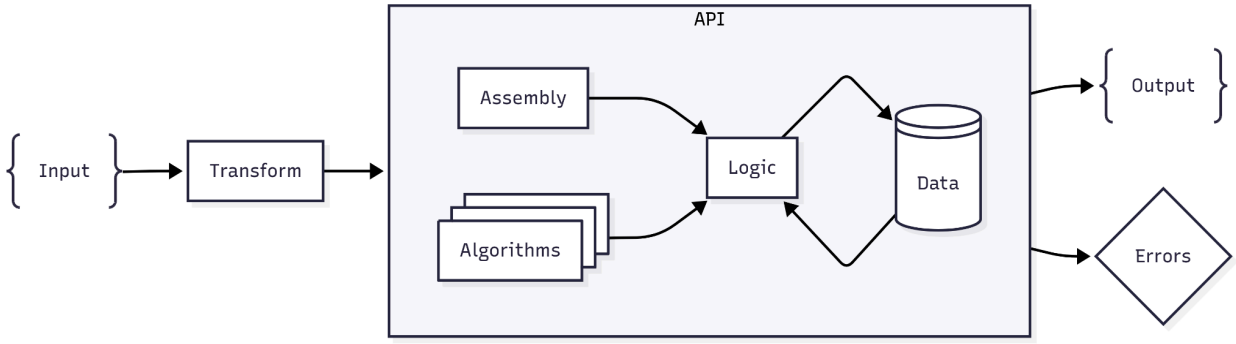


Fig. 3 FOUND Architecture

The two main modular algorithm types are edge detection and position determination, with each type containing multiple algorithms that may be linked together.

Calibration

The calibration pipeline takes in two orientations and saves the rotation transformation in quaternions in a `.found` file. This .found file is then used to transform the attitude from a star tracker into the FOUND camera's reference frame.

Distance

There are 2 atomic algorithms which get fed into the distance pipeline: Edge Detection (EDA), Distance Determination (DDA).

01. Edge Detection (EDA) transforms a picture to a collection of 2D `Points` on the picture that represent the planetary edge.

    a. `SimpleEdgeDetectionAlgorithm` (SEDA) works by identifying the ether (space) first, then identifying the contour of the ether that is shared by the planet as the planetary edge.

    b. `ZernikeEdgeDetectionAlgorithm` (ZEDA) ingests a pixel level edge detection algorithm (i.e. SEDA) to obtain a pixel level approximation of the edge of earth and then performs a sub-pixel edge correction using the moment based edge-orientation and offset.

02. `SpheroidPositionDeterminationAlgorithm` (SPDA), transforms the obtained `Points` and startracker quaternion into a `PositionVector` that represents the position of the satellite in the planetary coordinate system (celestial body is the origin). SPDA models Earth as a spheroid

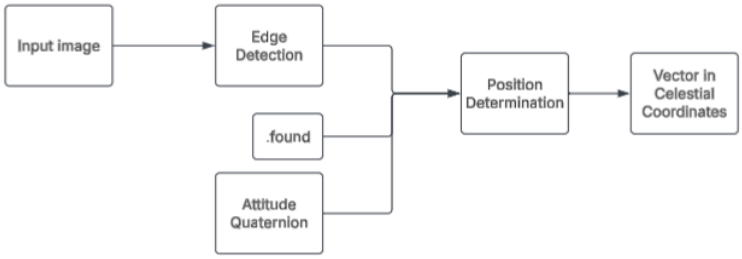


Fig 4. Position Determination Pipeline

Hardware

FOUND uses a visible-light camera (Ximea xiQ-S7) for edge detection and geometry-based altitude and orbital elements estimation, providing GPS-independent navigation. Visible light cameras offer better resolution which directly increases accuracy. Additionally, visible light cameras avoid active cooling which is necessary for infrared cameras. To compensate for sun glare and other optical effects, FOUND implements a sophisticated edge detection algorithm[7]. For HuskySat-2, the FOUND payload impacts design via camera alignment, pointing requirements, and interfacing with attitude output from both LOST and a truth measure.

2.3 - State of the Art

The unique challenge of lunar navigation and, on a broader scale, interplanetary navigation comes from the lack of ground and earth-based infrastructure that most earth-orbiting satellites rely on for navigation, including GPS and consistent ground ranging. A reliable long term GPS constellation would also be difficult to create with orbital instability around the moon.

Lunar navigation is a challenge that all lunar spacecraft must overcome. Previous missions have used a wide variety of technology to solve this problem, and the solutions shown in Fig. 6 below usually depend on the specific mission needs. These solutions include ground ranging, GNSS, Pulsar Navigation, and optical navigation, with most spacecraft combining multiple techniques to meet mission objectives.

3.0 CONOPS

3.1 - Concept of Operations (CONOPS)

HuskySat-2 (HS-2) operates autonomously between scheduled contacts while the ground team plans, authorizes, and reviews mission activities. The HuskySat-2 mission assumes a Low Earth Orbit (LEO) deployment with an orbital period of approximately 90 minutes. The spacecraft uses two top-level modes, Safe and Standby. Standby contains three prioritized submodes: Downlink, Science, and Charge. Orbital sunlight and eclipse are power, thermal, and observation conditions; they are not spacecraft states. System health takes priority over payload activity, and Safe may preempt any submode. When verifying the payload, the key constraints are power (see power budget), data storage capacity (see data budget), and ground station passes (see link budget).

3.1.1 Terminology

- Phase: A high-level segment of the mission lifetime, normally lasting days or weeks and bounded by major milestones or operational objectives. HS-2 phases are Deployment, Bus Commissioning, Payload Commissioning, Experiment, and Decommissioning.

- Mode: A coordinated spacecraft configuration selected by the flight state machine. HS-2 top-level modes are Safe and Standby. Standby contains the Downlink, Science, and Charge submodes.

- State: A subsystem or component configuration within a spacecraft mode or submode, including on/off status, rate, pointing behavior, and load. Sunlight, eclipse, ground-station visibility, and thermal conditions are environmental or contact conditions rather than spacecraft states.

3.1.2 - Mission Operations Plan

The Mission Operations Plan for HuskySat-2 outlines the operational framework to ensure successful execution of mission objectives: the demonstration of the LOST and FOUND. This plan leverages the satellite’s orbit characteristics, ground station passes, and operational modes to maximize data collection, system health monitoring, and experiment validation, while adhering to UNP guidelines and the mission’s requirements. The plan is based on the satellite’s deployment in Low Earth Orbit (LEO). It uses Leaf Space contact schedules for planning, but the spacecraft enters Downlink only after the Communications validates a beacon-response exchange and reports a contact event.

3.1.3 Orbit Requirements

The orbit requirements are defined to ensure mission success, aligning with scientific objectives and launch vehicle constraints. These are preliminary and subject to refinement based on launch provider specifications.

ORB-1	The satellite shall operate in a Low Earth Orbit at altitude between 400km and 600km [TBR].

3.2 - Mission Phases

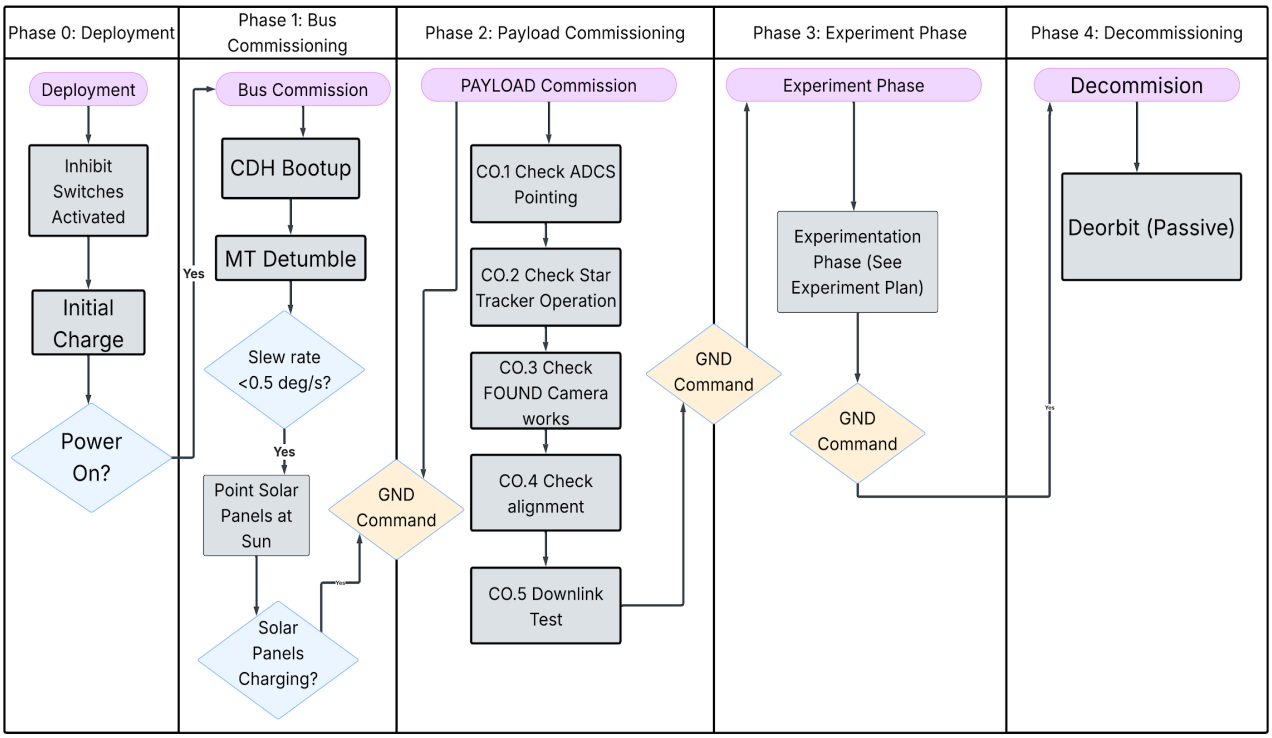


Fig. 5 CONOPS Mission Operation Plan

3.2.1 - Deployment (~ 5 min)

1. Inhibit switches will be activated. After the inhibits are activated, the satellite will power on in a minimal power (Safe) mode, sees that the panels are not deployed, and then proceeds to deploy them.
2. Initial charge: Solar panels begin charging upon exposure to sunlight. The BMS (Battery management system) initiates MPPT to charge the battery.
3. Power On Check: EPS verifies rail voltages and battery SOH using hardware logic.

3.2.2 - Bus Commissioning (~1 week)

1. CDH bootup: CDH boots flight computer, ADCS powers IMMU, magnetorquers, and sun sensors, PAY powers GNSS.
2. Magnetorquer detumble: ADCS engages magnetorquers to dampen tumble rates from worst case scenario 10 deg/s to experiment mode requirement, 0.5 deg/s, expected to take approximately 110 minutes.
3. Comms beaconing begins at ~45 minutes post deployment and transmits every second. The satellite has 2 patch antennas, enabling almost omnidirectional communications so that it is capable of closing a link even before detumbling.
4. Point solar panels at sun: magnetorquers orient satellite into optimal orientation, with 2 faces with solar panels facing the sun.
5. Solar panels charging: verify that the solar panels are generating power and charging the battery.
6. Sagitta star tracker turns on occasionally for ADCS. Satellite attitude will drift over time and so ADCS needs star tracker measurements to correct this.
7. Establish ground communications link then daily health and telemetry downlink.
8. Ground command to move into Payload Commission phase.

3.2.3 - Payload Commissioning (~1 week)

1. Check out 1: Check ADCS Pointing. CDH commands ADCS to slew to known attitude (nadir or star field) using magnetorquers and sensor feedback.
2. Check out 2: Check Star Tracker operation. Confirm LOST's payload hardware (Arcsec Sagitta) and software pipeline meet performance specs. CDH activates LOST camera and captures a starfield image. Process image through the pipeline to generate attitude quaternions. Compare with Arcsec Sagitta data for accuracy and validate runtime
3. Check out 3: Check FOUND camera works. Verify FOUND camera's hardware and initial operation for horizon tracking. CDH powers on FOUND camera and initiates a test image capture of the Earth's limb. Process the image to detect edges and log position data outputs.
4. Check out 4: Check alignment. Verify the angle between LOST and FOUND optical axes. CDH commands simultaneous image captures, software calculates attitude and compares with truth measure (Arcsec Sagitta). Angle within 0.04 degrees optimal (PAY-10)
5. Check out 5: Test Downlink. Verify the complete beacon-response sequence through the assigned Leaf Space station: receive the beacon, validate spacecraft identity, return the defined response, verify the CommsApplication contact event, then transmit images and data. The payload compresses images, sends them to CDH, CDH sends them to COMMS, and COMMS sends them to ground. A ground command is required to continue to the Experiment Phase.

3.2.4 - Experiment Phase (~2 weeks)

See section 3.4: Experiment Plan

3.2.5 - Decommission

The decommission phase is initiated upon ground command for the experiment phase being completed. First, the satellite is sent into safe mode to halt payload operations and minimize power consumption. Then, the satellite naturally decays over time, targeting re-entry within 25 years per debris rules.

3.2.5.1 - Phase Entrance Exit and Ground Gate Criteria

The following criteria make the phase narrative operational. A hold retains the current safe configuration and requires Flight Director review; a transition to Safe follows any protected fault or unavailable safety evidence.

CONOPS Table A: Mission Phase Entrance Exit and Ground Gate Criteria

Phase	**Entry and authority**	**Required operations and evidence**	**Exit, hold, or abort behavior**
Deployment (~5 min)	Launch separation and inhibit activation. No payload or Downlink authority.	EPS minimal-power startup; MPPT charging on solar exposure; verify rails and battery SOH.	Advance only after usable EPS health evidence. Hold in protected configuration / Safe on a fault or unavailable safety evidence.
Bus Commissioning (~1 week)	Entry after initial power-on health check. FD owns progression.	CDH boot; ADCS IMU, magnetorquer, and sun-sensor enable; 10 deg/s to 0.5 deg/s detumble (~110 min); ~45 min beacon; solar-pointing and daily health review.	Advance on verified health, detumble, charging, and approved commissioning evidence plus ground command. Hold for unresolved anomaly; Safe preempts.

CONOPS Table A: Mission Phase Entrance Exit and Ground Gate Criteria			
Phase	**Entry and authority**	**Required operations and evidence**	**Exit, hold, or abort behavior**
Payload Commissioning (~1 week)	Ground command after Bus Commissioning. Payload activity is limited to authorized checkouts.	CO.1 pointing; CO.2 LOST runtime; CO.3 FOUND limb/edge test; CO.4 0.05 degree alignment; CO.5 beacon-response and end-to-end data transfer.	Advance only when checkout evidence is accepted and ground commands Experiment Phase. Repeat checkout or return to the applicable safe/commissioning configuration on failure.
Experiment (~2 weeks)	Ground-enabled Experiment A, B, or C in Standby/Science with permissive power, thermal, storage, ADCS, payload, and truth-measure conditions.	Acquire the required image/truth/time data; run LOST and/or FOUND; preserve products and processing status in CDH; queue approved products.	Validated contact event preempts Science for Downlink. Guard failure returns to Charge; Safe preempts. Complete by success-criteria evidence or FD stop command.
Decommission	Ground command after mission completion.	Enter Safe, halt payload activity, minimize load, retain required final records.	Natural decay targets re-entry within 25 years. No return to mission operations without an explicit mission decision [TBR].

3.2.5.2 - Mission Phases Tables

0 = off
1 = on

Table 6: Mission Phases Overview

PHASE 0: DEPLOYMENT

	ADCS	CDH	PAY	EPS	COMMS	THR
Launch	0	0	0	0	0	0
Deployment	0	0	0	1	0	0
PHASE 1: BUS COMMISSIONING						
CDH Bootup	0	1	0	1	1	0
Detumble (MT)	1	1	0	1	1	0
Initial Charge	1	1	0	1	1	1
Downlink Status to Ground	1	1	0	1	1	1
PHASE 2: PAYLOAD COMMISSIONING						
CO.1	1	1	0	1	1	1
CO.2	1	1	1	1	1	1
CO.3	1	1	1	1	1	1
CO.4	1	1	1	1	1	1
CO.5	1	1	1	1	1	1

3.2.6 Operational Modes

3.2.6.1- State Machine

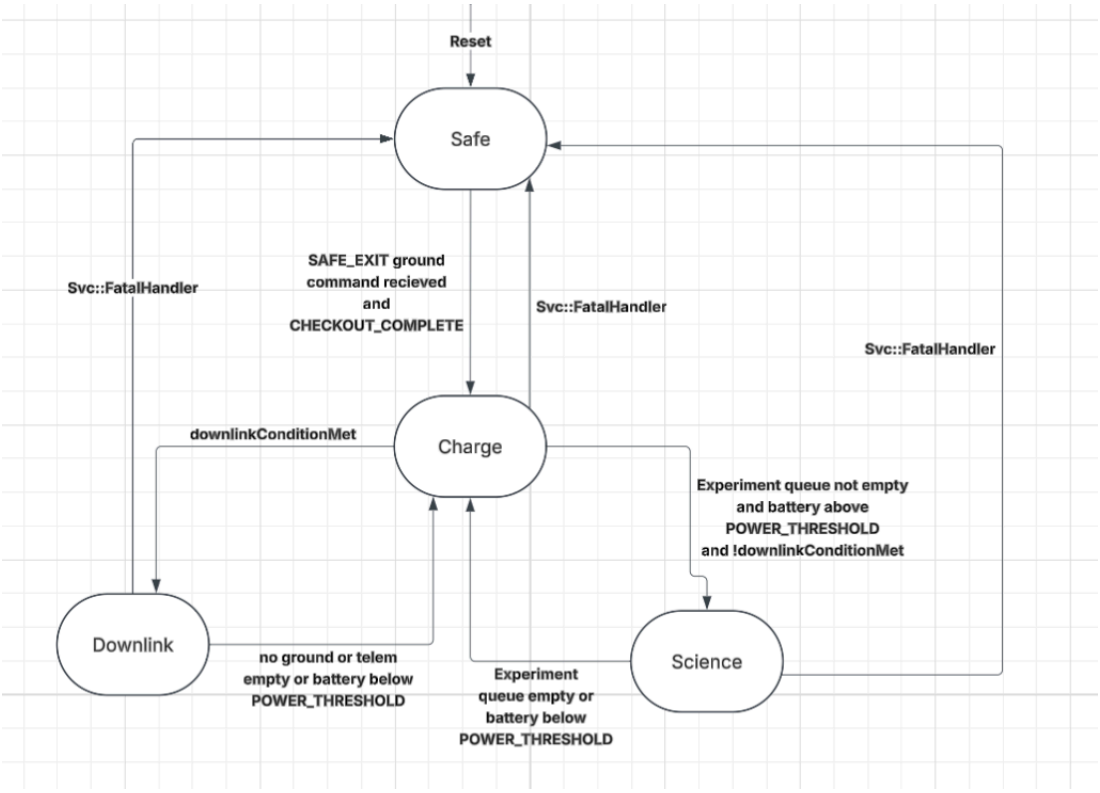


Fig. 6 Mode Machine

Table 7: Satellite Modes

Mode	Purpose	Entry Criteria	Exit Criteria
Standby/Science	Conduct the ground-enabled LOST or FOUND experiment.	• Ground-selected experiment A, B, or C • Candidate 85% SoC threshold [TBR] shall be replaced by a validated EPS energy guard • Sun-sensor check confirms the camera is not facing the Sun	• Candidate 50% SoC threshold [TBR], failed energy/thermal/attitude guard, or data storage at 90% [TBR] full -> Standby/Charge • Validated contact event -> Standby/Downlink • Safe preemption -> Safe
Safe	Low-power, minimum-load configuration for emergency protection and debugging.	• Satellite reboot • Validated critical-energy condition; legacy 30% SoC trigger retained as a candidate [TBR] • Protected system fault • Authorized SAFE command	• Authorized ground command after recovery evidence -> Standby/Charge [TBR]
Standby/Charge	Default low-activity configuration for power recovery, health monitoring, beaconing, and command reception.	• Science completion • Candidate 50% SoC threshold [TBR], data storage at 90% [TBR] full, or another non-safe guard failure • Default Standby entry	• Validated contact event -> Standby/Downlink • Ground enables an experiment and energy, storage, thermal, attitude, and sun-exclusion guards are permissive -> Standby/Science • Safe preemption -> Safe
Standby/Downlink	Support the active ground contact, command verification, telemetry, and queued data transfer.	• CommsApplication contact-established event after beacon-response validation • No Safe preemption; raw EPS/BMS, thermal, and storage guards permissive	• Contact-lost event, inactivity timeout, or session complete -> Standby/Charge, or return to eligible Science • Safe preemption -> Safe

3.2.6.2 Mode Transition and Flight Rule Baseline

This table complements Figure 6 and Table 7. It identifies the event source, active configuration, and required transition behavior. Sunlight and eclipse remain environmental inputs—not spacecraft modes.

CONOPS Table B: Mode Transition and Flight Rule Baseline			
Mode	**Entry trigger and source**	**Active configuration**	**Exit and precedence**
Safe	Authorized SAFE command; protected fault; validated critical-energy condition; satellite reboot. Sources: state machine, EPS/BMS, fault management, or ground command.	Minimum load, watchdog/recovery monitoring, low-rate beacon and command reception; payload off.	Exit only on authorized ground recovery after acceptable raw EPS/BMS, thermal, fault, and state evidence. Safe preempts every other mode.
Standby/Charge	Default Standby entry, science completion, contact completion/loss, or a non-safe guard failure.	Health monitoring, beaconing, command reception, power recovery, and solar pointing as needed.	Validated beacon-response contact event -> Downlink. Ground experiment enable plus permissive guards -> Science. Protected fault -> Safe.
Standby/Science	Ground-selected Experiment A, B, or C plus permissive raw energy/BMS, thermal, storage, ADCS, payload, Sun-exclusion, and truth-measure guards.	Approved LOST/FOUND camera and processing configuration; experiment pointing; CDH product storage.	Validated contact event -> Downlink. Guard failure, 90% storage candidate [TBR], or science completion -> Charge. Protected fault -> Safe.

CONOPS Table B: Mode Transition and Flight Rule Baseline			
Mode	**Entry trigger and source**	**Active configuration**	**Exit and precedence**
Standby/Downlink	CommsApplication contact-established event after the scheduled beacon-response validation, with no Safe preemption and permissive raw EPS/BMS, thermal, storage, and ADCS guards.	Command verification, prioritized telemetry, events, command responses, and queued file transfer using the selected SDLS framework.	Contact-lost, inactivity timeout, or session completion -> eligible Charge or Science. Protected fault -> Safe. Prediction alone does not enter Downlink.

3.3 - Operational States

Operational state selections are implemented through Safe and the Standby/Charge, Standby/Science, and Standby/Downlink submodes. Sunlight and eclipse are environmental inputs to the EPS and thermal logic; they are not spacecraft states. The matrices below define the expected subsystem configuration in each operational submode and retain [TBR] where a rate or recovery configuration remains unallocated.

An important note is that for components like sun sensors (photodiodes) and thermocouples, these components are always ‘active’ by nature. However, to read them, we have to power an ADC or thermal amplifier respectively, so we consider ‘On’ to mean they are actively being used.

3.3.1 Satellite State Matrix

Table 8: State Matrix

Component	Standby/Charge	Standby/Science	Standby/Downlink	Safe
ADCS	On; solar-pointing / detumble as required	On; experiment pointing	On; maintain link-compatible attitude	On; detumbling
Payload	Off	On	Off unless authorized for data recovery	Off

EPS	On; raw BMS/rail monitoring	On; enforce approved energy guard	On; raw BMS/rail monitoring	On; minimum-load protection
COMMS	Beacon, receive commands	Beacon, receive commands	Receive and transmit during validated contact	Low-rate beacon and receive commands
CDH	On; housekeeping and command processing	On; run payload pipeline and store products	On; command, telemetry, and file transfer	On; watchdog and recovery processing
Thermal	Heaters active	Heaters active	Heaters active	Heaters inactive

3.3.2 ADCS State Matrix

Table 9: ADCS State Matrix

Component	Standby/Charge	Standby/Science	Standby/Downlink	Safe
IMU	On; normal/low rate [TBR]	On; full experiment-support rate [TBR]	On; link-support rate [TBR]	On; minimum rate [TBR]
Sun sensor	On; solar-pointing and sun-exclusion monitoring	On; payload sun-exclusion monitoring	On; as required for attitude safety	On; conservative attitude monitoring
Magnetorquers	On; detumble or solar pointing as required	On; slew / hold experiment attitude	On; maintain link-compatible attitude	On for detumbling, then point towards sun for charge
Arcsec Star Tracker TM	Off	On; take star-field images, calculate attitude, send data to CDH	On; take star-field images, calculate attitude, send data to CDH	Off

3.3.3 CDH State Matrix

Table 10: CDH State Matrix

Component	Standby/Charge	Standby/Science	Standby/Downlink	Safe
Flight Computer	Monitor raw EPS/BMS, thermal, faults, commands, housekeeping, and low-rate telemetry	Run LOST and FOUND pipelines; store experiment data	Process commands and prioritized telemetry/file queue	Monitor watchdog timers, faults, and recovery commands

3.3.4 EPS State Matrix

Table 11: EPS State Matrix

Component	Standby/Charge	Standby/Science	Standby/Downlink	Safe
Solar Panels	Deployed; generate power when sunlit and support charge	Deployed; generate power subject to approved energy guard, monitor for low battery	Deployed; generate power when sunlit	; generate power when sunlit
BMS	On	On	On	On
PDS	On	On	On	On

3.3.5 Thermals State Matrix

Table 12: Thermal State Matrix

Component	Standby/Charge	Standby/Science	Standby/Downlink	Safe
Thermal Sensors (Thermocouples)	On	On	On	On

Passive MLI/Radiators [TBD]	Passive	Passive	Passive	Passive
Kapton Heaters	On if battery <5 [TBR] °C; off if battery <0 °C (priority)	On if battery <5 [TBR] °C; off if battery <0 °C (priority)	On if battery <5 [TBR] °C; off if battery <0 °C (priority)	Off

3.3.6 Payload State Matrix

Table 13: Payload State Matrix

Component	Standby/Charge	Standby/Science	Standby/Downlink	Safe
LOST Camera	Off	On; take star-field images and send to CDH	Off	Off
GNSS	On, collecting position data to correct IMU bias	On; collect position truth measurements and send to CDH	On, collecting position data to correct IMU bias	Off
FOUND Camera	Off	On; take Earth-limb images and send to CDH	Off	Off

3.4 - Experiment Plan

The following sections outline the different experiments planned to demonstrate the capabilities of the HS-2 payload, flowing down from the mission success criteria outlined in section 1.4. These experiments are intended to be completed as many times as outlined in the mission success criteria, and build upon each other in order of complexity (A is the simplest, then B, etc.). Any experiment that contains multiple success criteria counts towards each of them at the same time. These experiments will output data for error calculations, performed by the HS-2 ground team.

3.4.1 - Attitude Plan

The experimentation phase leverages the Attitude Determination and Control Subsystem (ADCS) to orient the satellite, aligning the payload imaging hardware with their respective targets while adhering to operational constraints. The ADCS employs a three-axis stabilized control strategy using magnetorquers, pointing towards Earth's limb for FOUND's camera and a star field for LOST's camera and the onboard star tracker. Attitude updates occur at 5 Hz, driven by the attitude algorithm. The Arcsec Sagitta star tracker has an FOV of 25.4 degrees.

3.4.1.1 - Horizon Detection for FOUND

The satellite identifies the horizon for FOUND by relying on ADCS to maintain an Earth-pointing attitude, where the horizon appears as a distinct edge in the camera's field of view. FOUND's edge detection algorithm (*CEDA/SEDA, Section 2.2.3)* processes these images and isolates the Earth's limb. Initial coarse pointing is achieved with ADCS's onboard GPS and magnetometer data [TBR], while the star trackers provide fine attitude knowledge.

3.4.1.2 - Star Field Acquisition for LOST

For LOST, the spacecraft achieves a clear view of the star field by slewing ADCS to a star-pointing attitude, avoiding Earth's limb and sun interference. LOST's centroiding (via center of gravity algorithm) requires at least 4 stars in its FOV, detected through a threshold-based star identification process (Tetra/Pyramid, 95% accuracy). LOST uses pre-loaded star catalogs and sensor's real-time feedback to adjust pointing, ensuring unobstructed views during data acquisition.

3.4.2 Experiments

Note that experiments are only able to be done when GND allows the satellite to enter experiment code (through a command) and when GND queues experiments through a command. GND signifies the type of experiment to run by telling the satellite which algorithms from LOST and FOUND to use, and gives a number of that experiment to run, which the satellite will perform when it enters Experiment mode. See the Command and Telemetry List (CTL) for more detail on the commands.

Table 14: Experiments

Experiment	Overview
A	Test accuracy of LOST.
B	Test accuracy of FOUND position vectors independent of LOST (Utilizing truth measure star tracker).
C	Test accuracy of FOUND position vectors dependent on LOST.

3.4.2.1 Experiment A: Test LOST

Table 15: Experiment A

Objectives	Test accuracy of LOST.
Description	Take a picture of the stars, record true attitudes, and record time. Run LOST. Downlink telemetry.
Success criteria	**MSC-2:** Determine with 99% power and 1% error rate if LOST calculates attitude of the satellite to within 30 [TBR] arcseconds 3-sigma **across-boresight.** **MSC-3:** Determine with 99% power and 1% error rate if LOST calculates attitude of the satellite to within 30 [TBR] arcseconds 3-sigma **around-boresight.** **MSC-4:** Downlink 1 image of the stars and 1 image of Earth's lit limb. **FSC-2:** Determine with 99% power and 1% error rate if LOST calculates attitude of the satellite to within 9 [TBC] arcseconds 3-sigma across-boresight. **FSC-3**: Determine with 99% power and 1% error rate if LOST calculates attitude of the satellite to within 45-50 [TBC] arcseconds 3-sigma around-boresight. **FSC-4**: Downlink and deliver 30 images for LOST and 30 images for FOUND. **FSC-5:** HS2 will report spread and bias for LOST and FOUND
Pipeline	1. Take picture on star tracker 2. Record the true attitude (truth measure output), and record time 3. Run LOST using same picture 4. Save output 5. Downlink output 6. Calculate accuracy on ground 7. If commanded, downlink image
Data output (downlinked to ground)	● Attitude measurements provided by LOST ○ Includes a measurement from each LOST algorithm ● Attitude measurements provided by truth measures (TM) ● Time stamp for LOST and Truth Measures (TM)

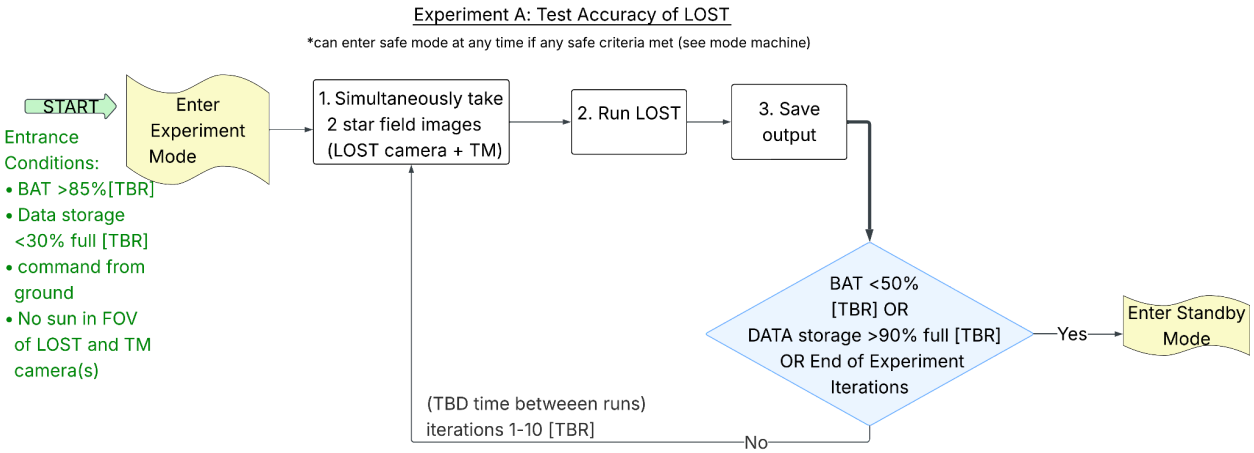


Fig 7. Experiment A

3.4.2.2 Experiment B: Test FOUND position vector from truth measure attitude

Table 16: Experiment B

Objectives	Test accuracy of FOUND position vectors.
Description	Take a picture of Earth's limb, calculate the true attitude and position vector. Use true attitude as input to FOUND. Run FOUND. Downlink telemetry.
Success criteria	**MSC-1**:Determine with 99% power and 1% error rate if FOUND calculates Earth's lit limb to be within the mesosphere 3-sigma. **MSC-4**:Downlink 1 image of the stars and 1 image of Earth's lit limb. **FSC-1**: Determine with 99% power and 1% error rate if FOUND calculates the satellites position within TBD meters 3-sigma **FSC-4**: Downlink and deliver 30 images for LOST and 30 images for FOUND. **FSC-5**: HS2 will report spread and bias for LOST and FOUND
Pipeline	1. Simultaneously take picture of Earth's limb, get an attitude from the truth measure, record true position, and time 2. Truth measure attitude + picture of Earth's limb -> run FOUND 3. Save output 4. Downlink output 5. Calculate accuracy on ground 6. If commanded, downlink image
Data output	• Attitude measurements provided by truth measure

(downlinked to ground)	• Position vector from FOUND ○ Includes all FOUND algorithms • Position vector from truth measure • Timestamp when measurements were taken

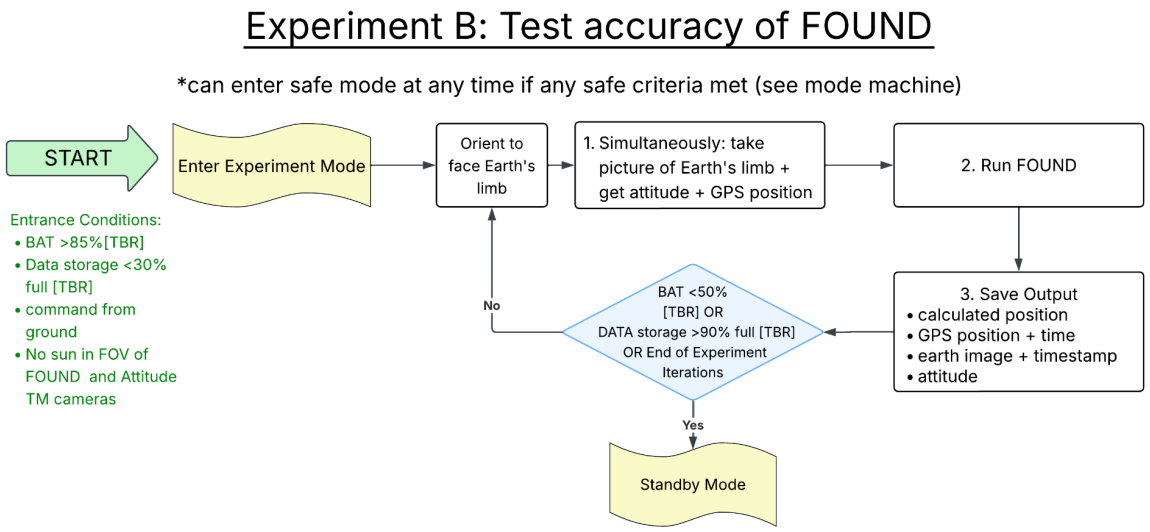


Fig 8. Experiment B

3.4.2.3 Experiment C: Test FOUND position vector with LOST attitude

Table 17: Experiment C

Objectives	Test accuracy of LOST. Test accuracy of FOUND position vector dependent on LOST.
Description	Take a picture of Earth's limb, a picture of the stars, and record attitude and position truths. Run LOST and pass its output into FOUND. Downlink telemetry.
Success criteria	**WIP**
Pipeline	1. Simultaneously take pictures, record truth measures, and record time 2. picture of stars -> run LOST 3. LOST attitude + picture of Earth's limb -> run FOUND 4. save output 5. downlink output 6. Calculate accuracy of LOST and FOUND
Data output (downlinked to ground)	• Pictures • Attitude measurements provided by LOST • Attitude measurements provided by truth measures • Position measurement from FOUND • Position measurement from truth measure • Time

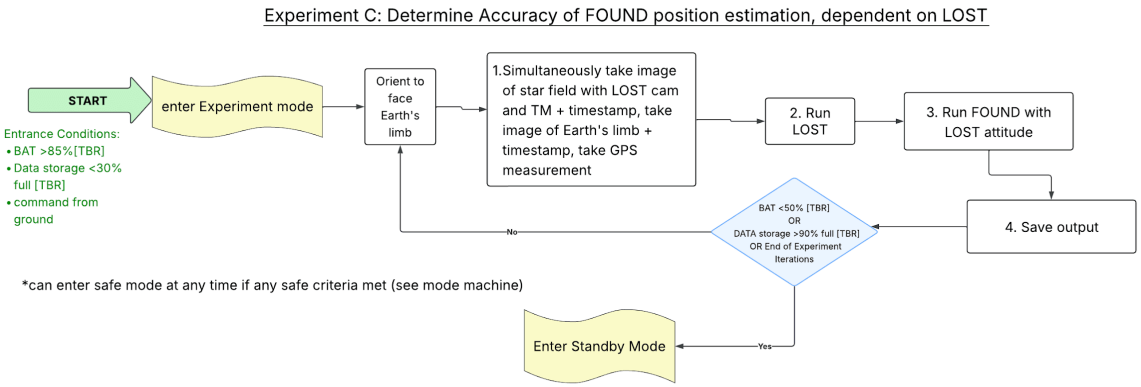


Fig 9. Experiment C

3.4.3 Error Calculations

This section outlines the inputs required in order to calculate the various performance metrics of LOST and FOUND. These calculations will be done by the ground station with telemetry from the satellite.

Table 18: LOST Performance Output

LOST Performance Output	Description	Needed values
Accuracy of Attitude	Angular error between the attitude given by LOST and the attitude given by the truth measure	• LOST Attitude in Celestial Frame • Truth measure attitude in Celestial Frame

Table 19: FOUND Performance Output

FOUND Performance Outputs	Description	Needed values
Accuracy of Position Vector	Percent/Distance between position vector given by FOUND and the position vector given by LOST in eclipse/light	• FOUND position vector spherical assumption • Truth measure position vector spherical assumption • Type of picture (sun/eclipse)

4.0 - Payload Overview

To meet mission success requirements the payload system will need two cameras, one for LOST and one for FOUND, as well as an attitude and an altitude truth measure. These cameras must meet the requirements for pixel resolution and focal length that were provided by the customers, LOST and FOUND. Additionally, the payload must know the angle between the two optical axes of the cameras within 1 degree (see error budget).

The payload responsibilities fall into three main categories: acquire input for LOST and FOUND, obtain ground truths to measure accuracy, and provide the software framework to run an experiment.

The HuskySat-2 mission advances low-cost, autonomous navigation for CubeSats through the demonstration of two open-source optical payloads developed by HSL. LOST (Lost Open-Source Star Tracking) and FOUND (Found Open-Source Universal Navigational Determiner). LOST provides value as an efficient star-tracker, achieving over 90% picture identification with attitude accuracy of approximately 45-50 [TBC] arcseconds around-boresight, and 9 [TBC] arcseconds cross-boresight in low cost setups (RaspberryPi), using minimal resources (35ms run time, <1MiB memory on Raspberry Pi). FOUND implements horizon tracking, estimating position with projected accuracy of 15-60 kilometers [TBR] in LEO, enabling GPS independent solutions for deep space or lunar environments.

The HuskySat-2 mission statement flows down to mission objectives, emphasizing the need for validation through in-orbit testing: MO-1 tests the accuracy of LOST attitudes, while MO-2 tests FOUND’s performance in estimating position vectors. These objectives drive Experiments A-C.

To support this payload, the HuskySat-2 integrates a 3U CubeSat structure, with thermal control for the cameras and processors, power allocation, and data handling. HS-2 development is driven by LOST and FOUND, driving the following design decisions: high resolution cameras and precision mounting, storage requirements to optimize compression and downlink, along with pointing requirements.

HS-2 Payload Requirements:

These requirements trace directly to the RVM, ensuring compliance with the mission objectives (determine accuracy of LOST and FOUND) by specifying sensor resolution, FOV constraints, computational resources, and alignment tolerances. They meet success criteria by enabling data acquisition and validation against truth measures.

PAY-1	Images of stars shall be captured with a camera with at least a 1024x1024, 8-bit pixel resolution.
PAY-2	The lens on LOST camera shall have an FOV between 20 and 25 degrees [TBR].

PAY-3	Images of Earth's limb shall be captured with a camera with at least a 1024x1024 pixel resolution.
PAY-4	The lens on FOUND camera FOV shall be between 70 and 90 degrees [TBR].
PAY-5	The payload shall determine the earth centered inertial (ECI) coordinates to 500m [TBR].
PAY-6	LOST compute shall have a clock rate 100Mhz and 1MB of RAM
PAY-7	FOUND compute shall have a clock rate [TBD] and [TBD] of RAM
PAY-8	The payload shall know the rotation between the true optical axis of the LOST and FOUND camera to within .05 degrees
PAY-9	The angle between the cameras used for LOST and FOUND shall be known to within 1 degree.
PAY-10	The angle between LOST and attitude TM shall be known to within 1 degree.
PAY-11	The angle between FOUND and the attitude TM shall be known to within 1 degree.
PAY-12	The satellite shall be capable of capturing images of a star field for LOST and images of Earth's limb for FOUND within 10 ms.
PAY-13	The satellite shall capture images using both LOST and star tracker truth measure synchronized within 15 arcseconds.
PAY-14	The position of the satellite shall be known to within 500m at the instance of a FOUND measurement.
PAY-15	The FOUND camera and GNSS receiver measurements shall be less than +-65 miliseconds apart
PAY-16	The FOUND camera and Star Tracker measurements shall be less than +-10 miliseconds apart
PAY-17	The FOUND camera shall blur the horizon across ≤ 2 pixels [TBR].
PAY-18	The FOUND camera shall image Earth ≥ 20dB [TBR] above the noise floor
PAY-19	The satellite shall maintain a keep-out FOV of TBD-TBD +- TBD degrees for payload cameras during experiment mode.
PAY-20	The satellite shall knows its attitude to +- TBD arcseconds
PAY-21	The satellite shall knows its position to +- TBD km

4.1 - Payload Hardware

Using the requirements set by the LOST and FOUND customer, the Husky Satellite Lab has selected the following hardware to support LOST and FOUND.

1. Arcsec Sagitta: COTS Star Tracker for attitude truth measure, providing 2 arcsec cross-boresight and 10 arcsec around-boresight accuracy to validate PAY-6.
2. Ximea xiQ-S7: COTS Camera for Earth limb imaging and starfield imaging, providing a variable FOV depending on the lens and satisfying PAY-1 and PAY-3.
3. Thorlabs MVL4WA Lens: COTS Lens for FOUND camera providing an FOV of 132.1 degrees to satisfy PAY-4.
4. Thorlabs MVL12WA Lens: COTS Lens for LOST camera providing an FOV of 38.5 degrees to satisfy PAY-2.
5. SkyFox Labs piNAV-NG GNSS: COTS GNSS receiver for position truth measure, delivering 10m accuracy to validate PAY-7.

The Payload design also incorporates precise mounting brackets to achieve the 1 degree alignment (PAY-10/11), verified via ground calibration and in-orbit payload checkouts (CO.4)

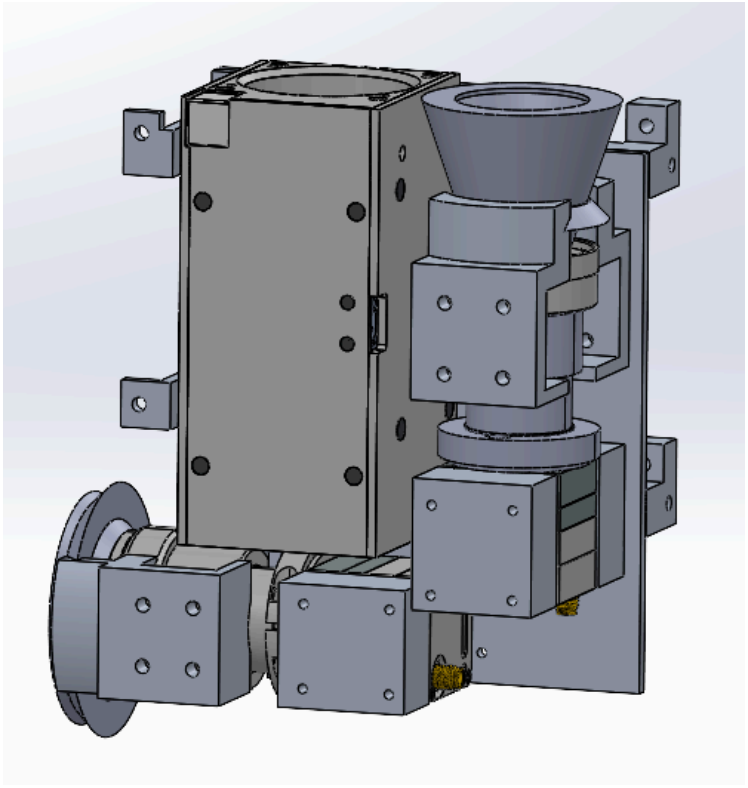


Figure 10. Payload Mounting

4.2 - Functionality

The truth data for LOST's attitude accuracy (target ≤9 arcsec cross-boresight / ≤45-50 arcsec around-boresight [TBC], FSC-2/FSC-3) will be provided by a dedicated onboard star tracker,

distinct from the ADCS. This reference star tracker, a COTS unit (Arcsec, Sagitta), serves as the truth measure during the Experiment Phase, allowing LOST's performance to be validated against a proven standard (3 degrees cross boresight, 30 degrees around boresight). This setup ensures independence from ADCS-derived estimates, enhancing reliability.

For FOUND, the GNSS provides position truth (10 m), enabling accurate assessment of 15-60km projections. The Flight Computer processes images, performing the LOST Pipeline and FOUND Pipeline, respectively. Payload functionality includes image compression (JPEG) and buffering for downlink, supporting FSC-4 (downlink images on request per FSC-4). This design supports the mission by demonstrating autonomous navigation through onboard processing, independent of GNSS for deep-space availability.

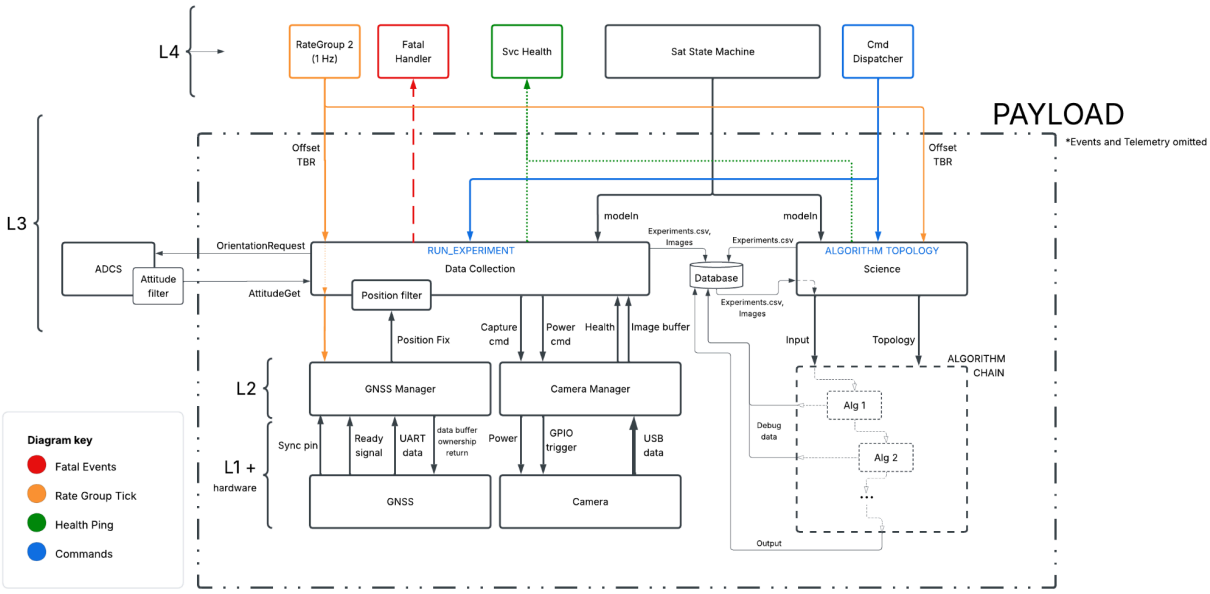


Figure 11. Payload software topology
This diagram shows how DataCollection and Science coordinate camera and GNSS inputs, experiment files, and algorithm execution while interfacing with the satellite state machine and command dispatcher.

4.3 - Interfaces

The two XIMEA cameras and eUSB storage device connect through the payload USB hub; the GNSS receiver uses LVTTL UART; the Sagitta truth star tracker uses full-duplex RS-485 carrying UART frames; and camera trigger and ready signals use GPIO. The XIMEA cameras operate with USB 3.1, and the BeagleBone Black from CDH uses USB 2.0; the USB hub IC on the PAY PCB handles this discrepancy, so we are able to communicate with the cameras through USB 2.0.

- Power: 5 V supplies the cameras, truth star tracker, eUSB device, and IMMU; 3.3 V supplies the USB hub and GNSS receiver. All interfaces use the spacecraft common ground.
- Data: USB carries camera commands and image data; full-duplex RS-485/UART carries Sagitta attitude truth; LVTTL UART carries GNSS position, velocity, time, and health data; GPIO carries camera trigger, ready, reset, and status signals.
- Thermal: LOST and FOUND camera thermocouples are two of the eight spacecraft thermal channels. Their differential signals are multiplexed, digitized by the shared MAX31856 interface, and read by CDH over SPI.
- Mechanical: the payload PCB occupies the upper end of the rail stack; GNSS mounts directly to it. LOST and FOUND mount to lateral plates using camera blocks and split baffle clamps, while the Sagitta truth sensor uses four brackets. CDH provides camera, GNSS, USB-hub, and IMMU recovery discretes.

These interfaces support the mission by ensuring payload data flows to COMMS and CDH for downlinking and analysis.

5.0 Satellite Bus

The HuskySat-2 satellite bus integrates attitude control, command and data handling, electrical power, communications, thermal control, and structures around the LOST and FOUND payloads. CDH coordinates the operational state machine and software applications; EPS supplies and monitors the regulated power rails; ADCS establishes the required attitude and Sun exclusion; COM provides the S-band command and telemetry path; THR monitors temperatures and controls the battery heater; and STR provides the load path, equipment mounting, and optical alignment interfaces. The subsystem interfaces below reflect the current ICD baseline and distinguish verified design values from remaining closure items.

The integrated PCB stack is assembled from bottom to top as the battery pack, BMS, PDS, MTA, S-band transceiver, hybrid coupler, CDH PCB, and payload PCB. A four-rod PC/104 compression system retains the stack. Most adjacent boards use a 0.6 in (15.24 mm) pitch; the battery-pack-to-BMS interface uses an approximately 4 mm spacer, the transceiver and coupler mate housing-to-housing, and the GNSS receiver mounts directly to the payload PCB.

5.1 - Attitude Determination and Control Subsystem (ADCS)

ADCS estimates spacecraft angular rate and attitude, detumbles the vehicle after deployment, supports experiment pointing, and enforces the payload Sun-exclusion constraint. The design uses magnetic actuation and combines inertial, magnetic, and coarse Sun measurements under CDH control.

5.1.1 - Requirements

ADCS-1	The ADCS shall be able to detumble to 0.5 deg/s from at least 10 deg/s of angular velocity from the spacecraft in at most 24 hours after deployment.
ADCS-2	The ADCS shall be capable of maintaining an angular velocity of less than 0.5 [TBC] deg/s while in experiment mode
ADCS-3	The ADCS shall have a pointing accuracy of at least 20 degrees while in experiment mode.
ADCS-4	The ADCS shall make sure the cameras are pointed at least 55 degrees away from the sun when cameras are on.
ADCS-5	The orientation of the ADCS actuators relative to the body frame shall be known within 3 degrees.
ADCS-6	The orientation between ADCS sensors (sun sensor, magnetometer, and IMU) relative to the body frame shall be known within 3 degrees.

5.1.2 - Hardware and Power

Magnetorquer assembly. The three-axis MTA contains two rod magnetorquers and one air coil driven through H-bridge voltage-amplifier electronics. Each rod is supplied from 5 V and draws approximately 0.49 W nominally. The air coil uses the 12 V boost rail, draws approximately 0.84 W nominally, and has a 13.2 W maximum allocation.

Inertial and magnetic sensing. A ruggedized VectorNav VN-100 IMMU provides angular-rate, acceleration, temperature, and integrated three-axis magnetic measurements. It is supplied from 5 V with a 0.22 W maximum draw.

Sun sensing. Three one-axis analog coarse Sun sensors are installed on the +X solar-panel face, -X solar-panel face, and FOUND camera face. Each sensor uses 3.3 V, draws approximately 0.5 mW, and produces two analog channels that are digitized by the CDH sensor ADC.

5.1.3 - Operational Behavior and Flight Software

ImmuManager and SunSensorManager sample the IMMU and six Sun-sensor ADC channels at 10 Hz and publish timestamped measurements. AttitudeFilter maintains the spacecraft state estimate. During deployment, BDotAlgorithm commands the MTA to reduce angular rate; during experiment operations, QuaternionPdAlgorithm and SlewRateAlgorithm calculate magnetic control commands for the requested pointing state. AdcsApplication coordinates the managers, applies mode commands from SatStateMachine, monitors health, and inhibits magnetic data use while the magnetorquers are energized.

The 20-degree experiment pointing requirement is the controlling MDD value. ADCS points the appropriate payload face toward the star field or Earth limb while the three coarse Sun sensors support the 55-degree exclusion check.

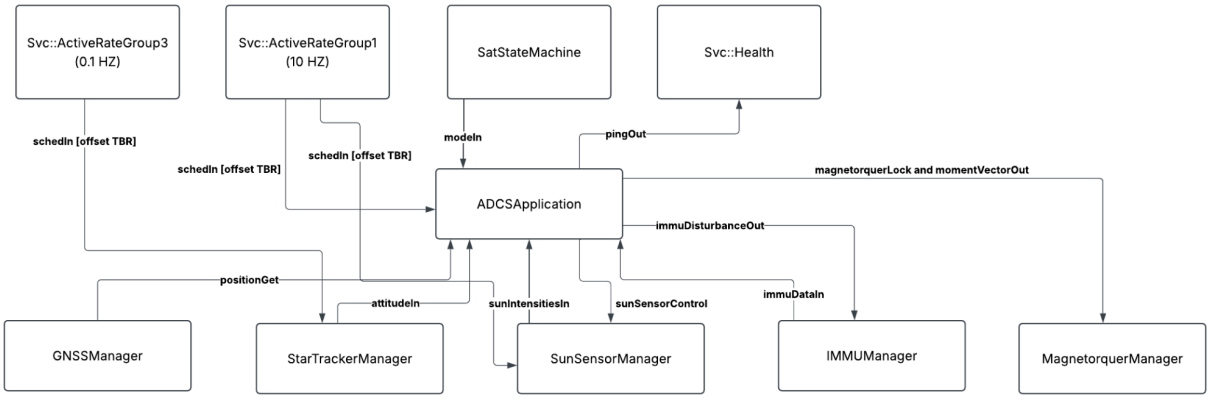


Figure 12. ADCS software topology

ADCSApplication is scheduled by the rate groups and state machine; it combines GNSS, star-tracker, sun-sensor, IMMU, and magnetorquer-manager interfaces to support attitude determination and control.

5.1.4 - Interfaces and Integration

Interface	Electrical or protocol detail	Purpose
CDH to MTA	Three 0-5 V PWM commands plus three GPIO direction/enable signals; allocated PWM range 1-50 kHz	Command the two rod magnetorquers and air coil
IMMU to CDH	LVTTL UART, nominally 115200 baud	Angular rate, acceleration, magnetic field, temperature, configuration, and status
Sun sensors to CDH	Six 0-2.4 V analog channels digitized through an MCP3208-class SPI ADC	Coarse Sun-vector measurement and exclusion checking
EPS to ADCS	12 V air-coil rail; 5 V rods and IMMU; 3.3 V Sun sensors; common ground	Subsystem power
CDH to IMMU	GPIO restore/reset discrete	Autonomous sensor recovery

The MTA PCB is retained in the rail stack between the PDS and S-band transceiver with standard 15.24 mm spacing. The IMMU mounts to a payload lateral plate and must be separated from the MTA sufficiently to avoid magnetic interference. Sun sensors mount on exterior faces. Magnetorquer heat generation is bounded by the actuator allocations; the IMMU operating range is -40 to 85 C and the Sun sensors are rated from -40 to 100 C. Manager state machines reset and retry failed interfaces and escalate repeated failures to AdcsApplication.

The ADCS provides stabilization using the magnetorquers, striving for a pointing accuracy of 20 degrees, per ADCS-3. It supports LOST by slewing to point at the stars for image acquisition, ensuring a clear view for centroiding and attitude estimation, with a 43 degree target. For FOUND, ADCS maintains a 43 degree pointing accuracy towards Earth’s limb to center the horizon within the FOUND camera’s 110-140 degrees FOV, enabling accurate edge detection and position vector calculation. ADCS also enforces a sun exclusion zone by utilizing the onboard coarse sun sensors (from the 2nd Space solar panels) and calculating the sun vectors, protecting the cameras for LOST and FOUND, aligning with the Experiment Phase attitude plan.

5.2 - Command and Data Handling (CDH)

The CDH, based on a BeagleBone Black Industrial, handles the compute for the ADCS, thermal, and payload control loops, as well as the LOST and FOUND algorithms. It also provides hardware peripherals for the IMU, GNSS, Sagitta, sun sensors, thermocouples, SSD, EnduroSat S-Band transceiver, ADCS H-bridges, PDS watchdog signal, and connection to the BMS board. The BeagleBone Black Industrial will also run the flight software, developed in C++ utilizing the F' framework from NASA JPL.

To account for the compute limitations, we identified heavy loads as: LOST/FOUND processing, image compression, encryption, and ADCS control loops/algorithms. We handle this by only running image compression and encryption during downlink mode, and LOST/FOUND during science mode. In addition, we will [TBR] have a PREEMPT-RT patch on the OS to make the scheduler more similar to an RTOS, and [TBR] switch from Debian Linux to Buildroot Linux for less kernel overhead. Testing still remains to be done once flight software is complete to ensure we meet the desired compute.

CDH manages onboard processing and data storage for experiment images, first downsampling them, and then storing them as raw, uncompressed bytes (~1.2 MB each) rather than JPEG, since compression isn't feasible on this hardware. With 64 GB of total storage and 56 GB reserved for image storage, CDH can store up to approximately 45,000 images, along with telemetry, interfacing with COMMS for downlinking.

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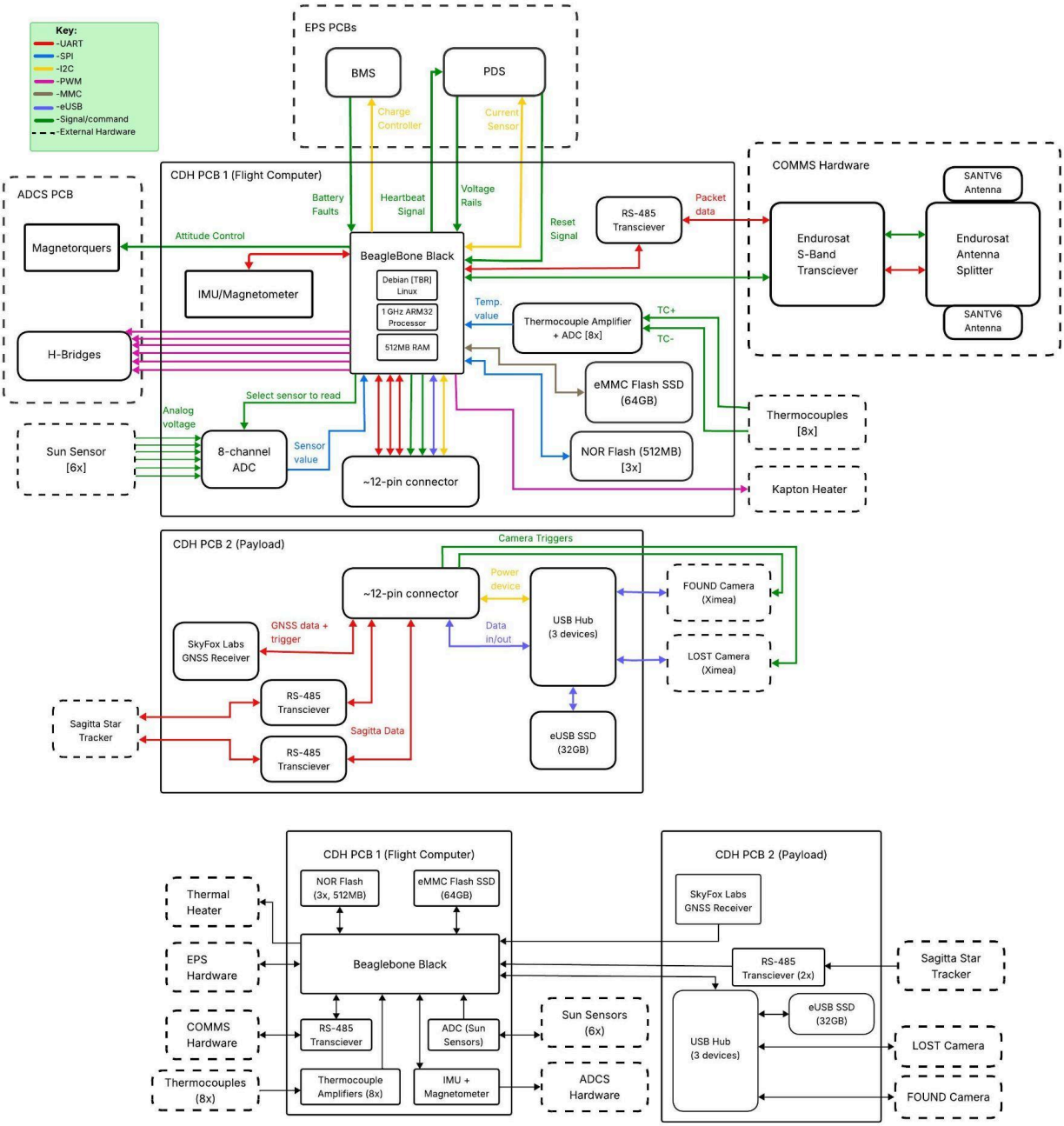


Figure 13. Flight Computer Architecture

The CDH contains the following components as described in the block diagram above:

- Communications Receiving Manager
- Communications Transmitting Manager
- Flight computer storage

- State Machine
- Payload Storage
- ADCS software
- Payload software
- Thermal software
- EPS software

5.2.1 - Requirements

CDH-1	The flight computer shall implement the state machine for the satellite's operational modes, as specified in the Mission Design Document.
CDH-2	The flight computer shall provide at least 64 GB [TBR] of non-volatile storage for payload data, telemetry, and software.
CDH-3	The flight computer shall interface with PAY as per the PAY ICD
CDH-4	The flight computer shall interface with ADCS as per the ADCS ICD.
CDH-5	The flight computer shall interface with Thermal Sensors as per the Thermal ICD.
CDH-6	The flight computer shall interface with EPS as per the EPS ICD.
CDH-7	The flight computer shall interface with COMMS as per the COMMS ICD.
CDH-8	The flight software shall package all telemetry as per the CTL.
CDH-9	The flight software shall calculate and monitor Health Metrics as per UNP12-68 and UNP12-69.
CDH-10	The flight computer shall detect and respond to subsystem faults in accordance with the spacecraft FDIR strategy [TBD].
CDH-11	The flight computer shall transition the spacecraft to safe mode for faults designated as requiring safe-mode entry by the FDIR strategy [TBD].
CDH-12	The satellite shall be capable of storing all LOST and FOUND images captured over the past 24 [TBR] hours in the onboard database
CDH-13	The flight computer shall be capable of executing the flight software defined in the Software Design Document (SDD).
CDH-14	The flight computer shall be capable of executing the LOST payload software required to support the experiments defined in the Payload Experiment Requirements [TBD].

CDH-15	The flight computer shall be capable of executing the FOUND payload software required to support the experiments defined in the Payload Experiment Requirements [TBD].

5.2.2 - Hardware Power and Storage

Flight-computer assembly. The CDH assembly contains the BeagleBone Black Industrial, a custom CDH PCB, and a USB cape. The custom PCB provides the eMMC interface, eFuses, sensor ADCs, RS-485 transceivers, GPIO, PWM, SPI, I2C, and UART signal conditioning required by the spacecraft interfaces.

Power. The itemized ICD allocation is 1.5 W typical and 2.3 W maximum at 5 V for the BeagleBone, approximately 0.011 W at 5 V for the CDH PCB circuitry, and approximately 0.504 W typical and 0.753 W maximum at 3.3 V for the remaining CDH electronics.

Storage. A 64 GB eMMC device provides 64 GB total non-volatile storage. Of this, 56 GB is reserved for payload data. Each camera acquisition is approximately 3.9 MB before processing; CDH downsamples the image to approximately 1.2 MB and stores the resulting uncompressed byte array. Allowing for filesystem, telemetry, and database overhead, the allocation supports approximately 45,000 stored images. A 32 [TBR] microSD card will be placed in the SD card slot of the BeagleBone Black, which will be secured through staking and a structural latch on the BeagleBone. It will be used primarily for booting the OS, with backups being stored in the SSD. This is discussed more in the SDD.

5.2.3 - Flight Software and Fault Handling

The flight software runs on the BeagleBone Black Industrial. SatStateMachine executes at 1 Hz and distributes ADCS, data-collection, science-processing, communications, and thermal modes. It receives orbit/contact, communications-readiness, downlink-queue, power, and health information and implements the SAFE_MODE, SAFE_EXIT, CHECKOUT_COMPLETE, and RESET command paths. F Prime CmdDispatcher routes commands; TlmChan and the packetizer collect telemetry; EventManager records events; Health pings active components; RateGroupDriver schedules periodic work; Version reports the build; and AssertFatalAdapter routes framework assertions into the fatal-event path.

Implemented recovery mechanisms include manager-level reset/retry state machines, F Prime health pings, explicit subsystem reset discretes, the EPS hardware watchdog, and commanded Safe-mode entry. These mechanisms support fault response; additional discussion for FDIR is present in the Software Design Document (using the F’ FatalHandler component).

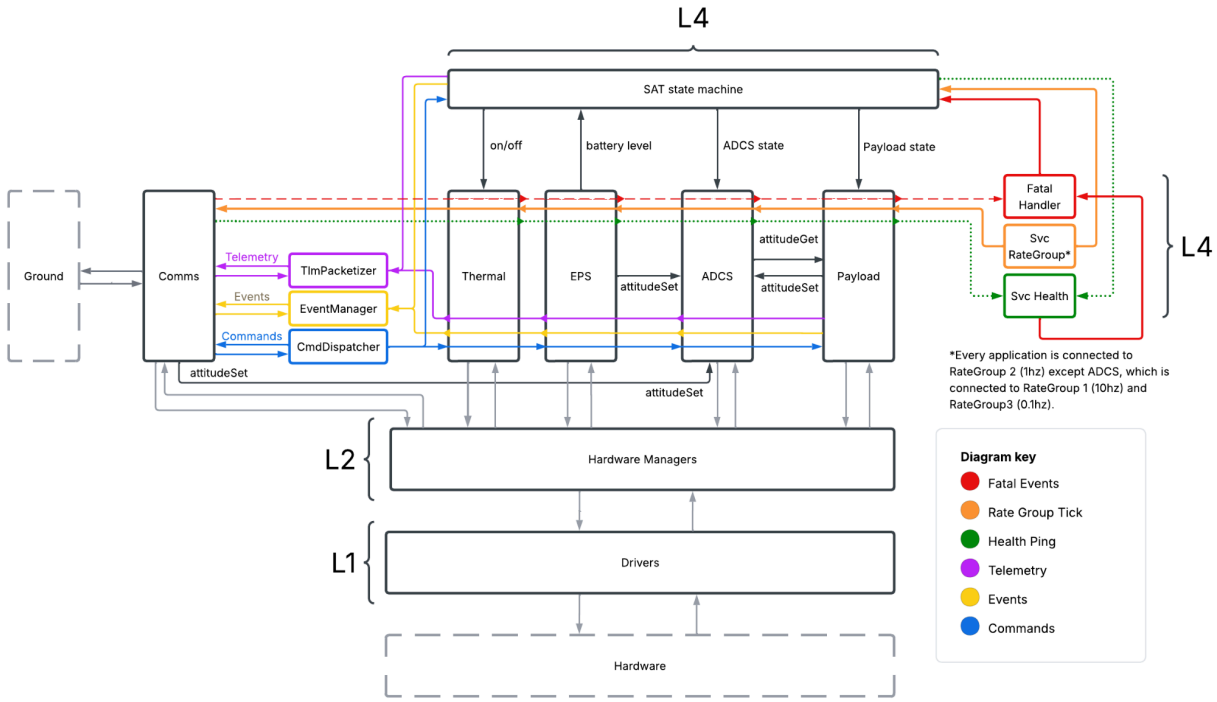


Figure 14. CDH software topology

The top-level SatStateMachine coordinates ADCS, EPS, thermal, payload, and communications applications, with command, telemetry, event, health, rate-group, and fatal-handling services providing common control and fault paths.

5.2.4 - Interfaces and Integration

Connected function	Interface	Data or control exchanged
LOST and FOUND cameras	USB; negotiated generation [TBR]	Camera commands, trigger coordination, and acquired image data
Sagitta truth star tracker	Full-duplex RS-485 with UART framing; 921600 baud allocation	Attitude quaternion and timing data
GNSS receiver	LVTTL UART, 9600 baud baseline	Position, time, velocity, status, voltage, current, and temperature
ADCS	UART, SPI/ADC, PWM, and GPIO	IMMU and Sun data, actuator commands, and recovery signals
EPS	I2C at 100 kHz plus GPIO	Battery and rail monitoring, watchdog heartbeat, reset, and panel deployment
COM	Half-duplex RS-485 carrying UART frames	Uplink commands and downlink telemetry/files

Connected function	Interface	Data or control exchanged
THR	SPI Mode 0, GPIO multiplexer/data-ready, and PWM	Digitized temperatures and heater duty-cycle control
Storage	eMMC and USB	Flight software, telemetry, events, and payload products

CDH is retained in the rail stack between the hybrid coupler and payload PCB at the standard 15.24 mm pitch.

5.3 - Electrical Power System (EPS)

The EPS delivers 3.3V, 5V, and 12V rails utilizing the power budget to supply subsystems with power. It uses 16 (TBR) solar cells, 2 (TBR) faces of coverage, generating ~12.124 (TBR) W per orbit. The EPS also utilizes a 75 Wh Li-ion battery, ensuring adequate power during eclipse phases. EPS power cycling supports payload checkouts and experiment modes, with watchdog hardware to maintain safe operation. The system combines the deployable solar array and battery pack with a BMS for charging and protection and a PDS for conversion, distribution, current monitoring, overcurrent protection, and watchdog-based reset.

HS-2 shall treat state of charge as an estimated onboard value, not a directly measured telemetry field. The estimator may begin as a voltage-to-SoC lookup, but the 100 percent and empty endpoints, temperature compensation, load dependence, update rate, estimator-validity criteria, and Safe/Science/Downlink/recovery thresholds remain TBR pending EPS charge-cycle characterization. Raw battery voltage, temperature, rail current, charge status, and BMS protection indications shall remain available for safety decisions even if the estimate is invalid.

5.3.1 - Requirements

EPS-1	The EPS shall supply each of the subsystems with power at the voltages outlined in the Power Budget.
EPS-2	The solar panels shall provide a minimum average power output of 12 W [TBR] during the sun period once the satellite has detumbled.
EPS-3	The EPS shall supply a minimum 4W-hr of energy to the satellite during data acquisition and transmission.
EPS-4	The EPS shall relay battery pack state of charge and current draw data from each voltage rail to the flight computer.
EPS-5	The EPS shall perform a full bus reset if no heartbeat signal is received from the flight computer after 1 minute.
EPS-6	The EPS shall be capable of resetting components listed in the ICD if instructed by the flight computer.

EPS-7	The solar panels shall charge the battery pack with 60 Wh of energy over 72 hours after deployment, assuming worst case angular rotation of 10 deg/s along the Z axis.

5.3.2 - Hardware and Power Architecture

Solar array. The current baseline uses 2NDSpace Drop-3 deployable panels. The array-to-charge-controller interface is approximately 16 V, 8.33 W typical, and 17.25 W peak. Final cell count, deployed area, and orbit-average generation remain tied to the updated power budget and as-built array configuration.

Battery Management System. The BMS uses Samsung INR18650-35E lithium-ion cells and a BQ25756E MPPT battery charger. The battery-to-PDS interface is approximately 24 V with 8.33 W typical and 17.25 W peak power in the ICD allocation. Inhibits prevent unintended activation during integration and launch.

Power Distribution System. The PDS converts the battery bus into regulated 12 V, 5 V, and 3.3 V rails. An INA3221 monitors rail voltage and current, eFuses provide current limiting and protection, and a TPS3431-class hardware watchdog supervises the CDH heartbeat.

5.3.3 - Monitoring Control and Fault Handling

MpptManager polls the BQ25756E at 1 Hz over a 100 kHz I2C bus and reports battery voltage, current, input voltage/current, charging state, charger flags, and fault flags. CurrentSensorManager polls the INA3221 at 1 Hz over the same bus and reports voltage and current on the 12 V, 5 V, and 3.3 V rails. EPSApplication combines these measurements for SatStateMachine, applies configurable warning and critical thresholds, and forwards the panel-deployment request to DeployPanelsManager.

WatchdogPinger produces an active-high 1 Hz heartbeat with a pulse width below 1 ms. If the heartbeat is missing for 60 seconds, the PDS asserts an active-low reset to CDH. We have verified that boot-time for the BeagleBone Black is less than 60 seconds. Raw battery voltage, current, charging state, temperature, rail measurements, and protection flags remain available even when the derived state-of-charge estimate is invalid.

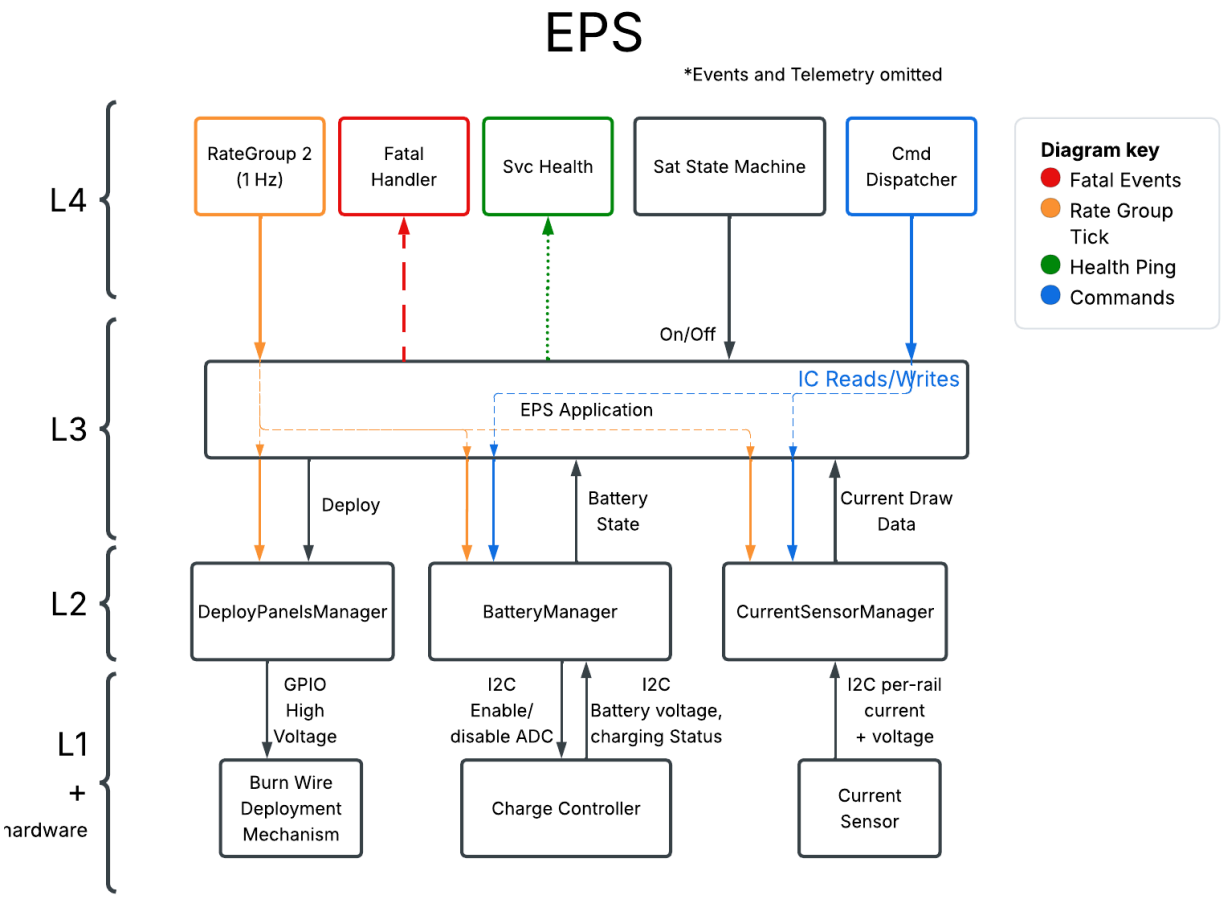


Figure 15. EPS software topology

EPSApplication connects battery, current-sensor, and panel-deployment managers to the state machine, health, rate group, and command dispatcher; the managers bridge flight software to charge, rail-monitoring, and deployment hardware.

5.3.4 - Interfaces and Integration

Interface	Implementation	Purpose
Solar array to BMS	Approximately 16 V; 8.33 W typical, 17.25 W peak	Battery charging through MPPT
Battery to PDS	Approximately 24 V inhibited bus	Stored-energy delivery
PDS to spacecraft	Regulated 12 V, 5 V, and 3.3 V rails	Subsystem power distribution
CDH to BMS/PDS	100 kHz I2C, 1 Hz polling	Charge-controller commands and battery/rail telemetry

Interface	Implementation	Purpose
CDH to watchdog	Active-high GPIO heartbeat at 1 Hz; pulse below 1 ms	Detect loss of flight-computer scheduling
PDS to CDH	Active-low GPIO reset after 45-60 s timeout	Hardware recovery
CDH to deployment circuit	GPIO	Command the solar-panel burn wire

The battery pack is the lowest secondary-structure assembly. It is followed by BMS with an approximately 4 mm spacer, then PDS and MTA at the standard 15.24 mm pitch. The battery is the most thermally constrained EPS element and is maintained within 0-45 C by THR with a Kapton heater.

5.4 - Communications (COMMS)

The Communications (COMMS) subsystem of HuskySat-2 is designed to enable reliable data exchange between the satellite and ground stations, supporting mission objectives.This subsystem ensures the uplink of commands, downlink of telemetry, and transmission of experiment data (e.g., LOST/FOUND images and quaternions) to facilitate real-time monitoring, health assessment, and scientific analysis. One EnduroSat transceiver feeds two SANTV6 wideband patch antennas through an EnduroSat hybrid coupler, providing antenna diversity while retaining a single radio data interface to CDH.

The following diagrams illustrate the design of the Communication Subsystem (COM) for HuskySat-2. The figures include an overview of the COM hardware and software design for the system.

Figure 16 provides an overview of the COMMS hardware. In regards to downlink, the RS-485 transceiver on the CDH PCB will deliver RS-485 signals to the Endurosat S-Band Transceiver to downlink images, log files, and telemetry. These downlink signals are then turned into S-Band RF signals by the S-Band transceiver and sent over MMCX connections to the Endurosat Antenna Splitter for the Endurosat Wideband Patch Antennas (SANTV6 model) to transmit towards the ground station.

For uplink, the SANTV6 patch antennas will receive the uplinked RF signals that may carry either files or commands for the satellite to process and transfer them over the MMCX connection to the transceiver. The transceiver will then forward these signals to the CDH subsystem through the RS-485 transceiver.

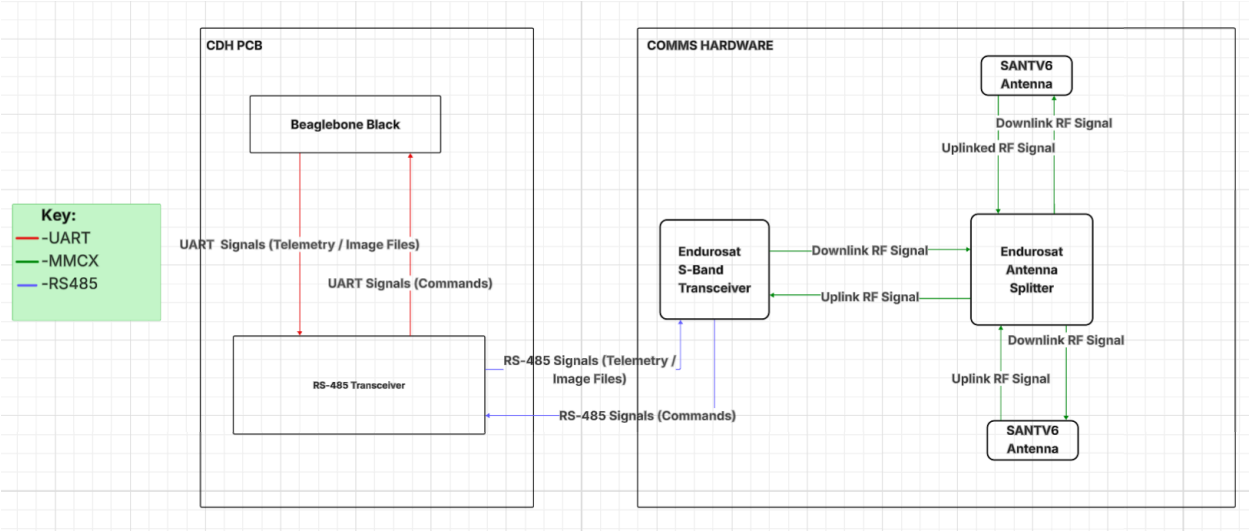


Figure 16, COMMS hardware

Figure 17 depicts the COMMS software architecture. The CDH software subsystem is responsible for providing real-time telemetry to the ComCCSDS subtopology which frames telemetry packets into the CCSDS TM Transfer Frame protocol (CCSDS 132.0-B-3). These telemetry frames are then forwarded to the TmtcRadioManager. The TmtcRadioManager is the interface between the CDH software and the S-Band transceiver. The TmtcRadioManager is responsible for delivering telemetry to the transceiver and receiving uplinked commands and files from the transceiver over UART. The Communication Application is responsible for managing when and what telemetry the satellite will downlink to the ground station.

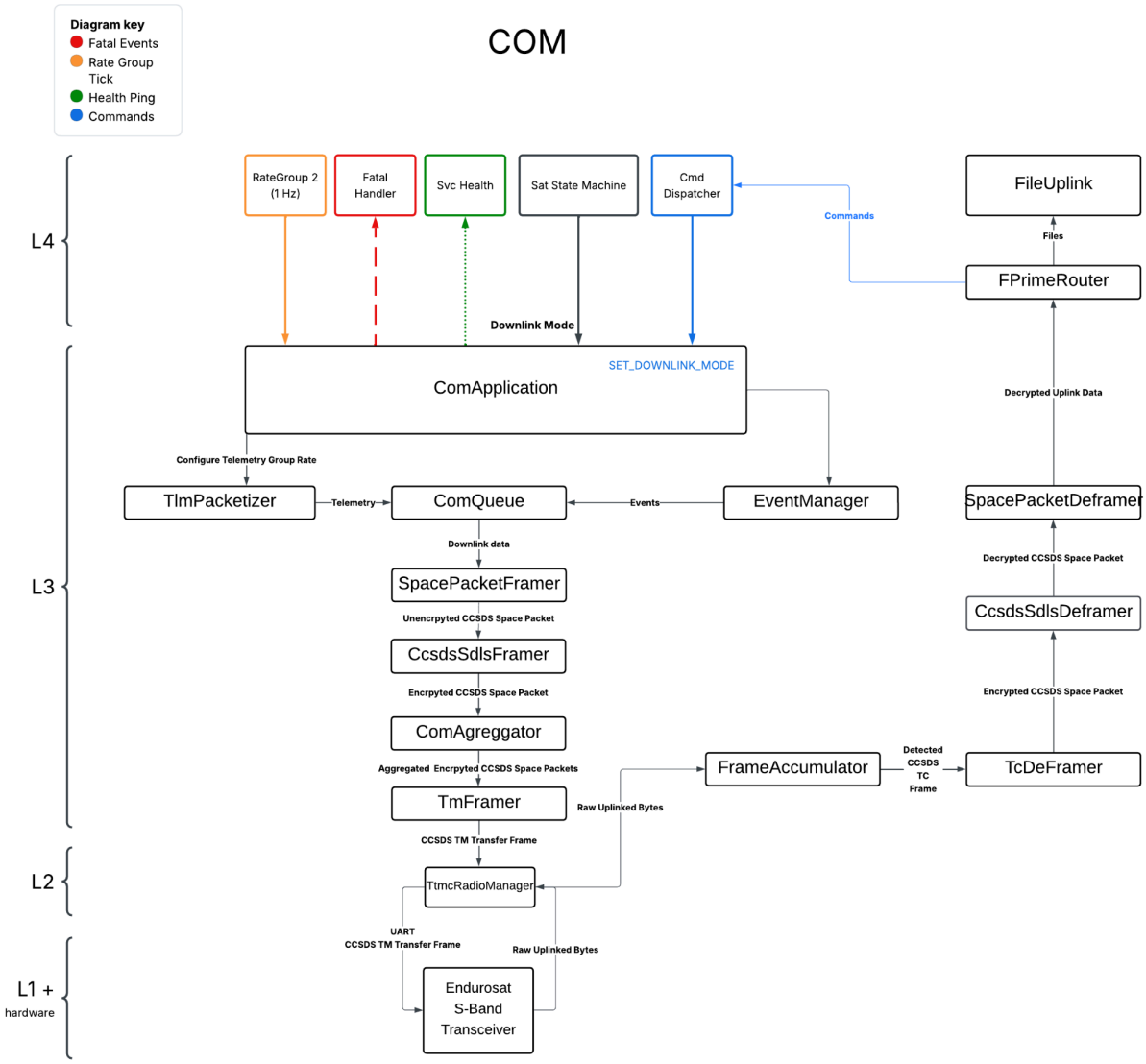


Figure 17, COMMS Software

5.4.1 - Requirements

COM-1	The Communication System shall maintain an effective telemetry downlinking data rate of 50 kbps [TBR].
COM-2	The Communication System shall be capable of receiving commands at a minimum effective rate of 312 bps [TBR].
COM-3	The Communication System shall have an antenna with a gain of at least 5 dB (TBR).

COM-4	The Communication System shall downlink images on command at a rate of 20 [TBR] kbps.

5.4.2 - Hardware Power and Radio Link

Transceiver. The EnduroSat S-band transceiver operates from the 12 V rail. It draws approximately 1.66 W in receive mode and up to 10.4 W in transmit mode. The CDH electrical connection is half-duplex RS-485 carrying UART frames.

Antennas and coupler. Two SANTV6 wideband patch antennas connect to the single transceiver through the hybrid coupler. The antenna gain and resulting link margins are present in the Link Budget.

Throughput. The radio's nominal downlink rate is 50 kbps. Forward error correction consumes approximately half of that channel capacity, yielding the 25 kbps effective downlink baseline. The minimum uplink baseline is 3.3 kbps, as outlined in the Data Uplink budget.

5.4.3 - Flight Software and Data Flow

ComApplication selects one of four transmission modes: BEACON, STANDARD_DOWNLINK, STORED_PLAYBACK, or NO_DOWNLINK. It sets telemetry packetization rates, reports the active mode, and responds to SatStateMachine and health pings. TmtcRadioManager transfers the framed byte stream between flight software and the transceiver over the UART/RS-485 path.

F Prime FileDownlink and FileUplink manage queued file transfer. ComQueue prioritizes telemetry, events, and file packets. SpacePacketFramer, TmFramer, FrameAccumulator, TcDeframer, SpacePacketDeframer, FprimeRouter, and CmdDispatcher implement the CCSDS TM downlink and TC uplink path. CcsdsSdlsFramer, CcsdsSdlsDeframer, and SdlsRouter provide the flight-side SDLS insertion points. Security associations, keys, ground interoperability, key-management procedures, and protection-failure handling remain TBR.

5.4.4 - Interfaces and Integration

Interface	**Implementation**	**Purpose**
CDH to transceiver	Half-duplex RS-485 carrying UART frames; documented UART allocation 9600-115200 baud	Uplink commands and downlink telemetry/files
PDS to transceiver	12 V and common ground	Radio power
Transceiver to coupler	MMCX/coaxial RF connection	Split transmit and receive RF energy
Coupler to antennas	Two coaxial RF paths	Connect the two SANTV6 patches

Interface	Implementation	Purpose
THR monitoring	Thermocouple at the communications antenna, digitized by the shared THR ADC chain	Temperature monitoring

The transceiver is retained above the MTA at the standard 15.24 mm pitch. The hybrid coupler sits directly on the transceiver housing without a standoff, and the standard pitch resumes between the coupler and CDH. Both patch antennas require structure-mounted brackets and unobstructed RF fields of view. Connector clearances at the direct-contact interface and final antenna-bracket details remain open mechanical items.

5.5 - Thermal (THR)

The thermal subsystem employs both active (Kapton heaters) and passive control (MLI, emissivity coating) to maintain components per the thermal budget. The system ensures that the EPS battery pack stays within its temperature range of 0-45 C. The design uses eight thermocouple channels, a multiplexed MAX31856 thermocouple amplifier/ADC, and a PWM-controlled Kapton heater. CDH executes the sensing and control software; EPS supplies sensor and heater power.

5.5.1 - Requirements

THR-1	The thermal subsystem shall maintain the temperature of the battery management system within 0 to 45°C during the mission lifetime.
THR-2	The thermal subsystem shall maintain the satellite's solar panels to be within their operating temperature range of 10 to 65°C
THR-3	The thermal subsystem shall maintain all other internal components of the satellite within their operating range of -30 to +40 °C.
THR-4	Thermal shall maintain all other external components of the satellite within their operating range of -40 to +90°C.

5.5.2 - Hardware and Sensor Allocation

Thermocouples and amplifier. Eight differential thermocouple channels monitor the BeagleBone CPU, LOST camera, FOUND camera, battery pack, 12 V PDS converter, 5 V PDS converter, 3.3 V PDS converter, and communications antenna. A MAX31856-class amplifier digitizes the selected channel and provides cold-junction temperature and open/short fault flags. Locations:

- LOST Camera

- FOUND Camera
- Battery Pack
- Buck Converters (3.3V, 5V, 15V)
- CDH Computer
- COM Patch Antenna

Battery heater. The Kapton heater is supplied from 12 V through the PDS. Its allocation is 4.84 W nominal, 5.32 W maximum, and 1.60 W in Safe mode. CDH controls the heater through a hardware PWM output.

5.5.3 - Control Software and Fault Handling

TemperatureSensorManager selects one of eight inputs with three GPIO address lines, reads the MAX31856 through SPI Mode 0 at up to 5 MHz, monitors the active-low data-ready line, and reports per-sensor temperature and validity. HeaterManager accepts a commanded duty cycle, clamps it to 0-100 percent, programs a 1-10 kHz PWM output, and reports PWM failures or commands received outside the RUN state.

ThermalApplication executes at 1 Hz, receives its mode from SatStateMachine, evaluates sensor validity and temperature limits, and applies a PID heater command when active heating is permitted. Ground commands can force or clear a heater-duty override. Invalid sensors, insufficient valid measurements, threshold crossings, SPI failures, and PWM failures generate events for CDH and can inhibit active heating.

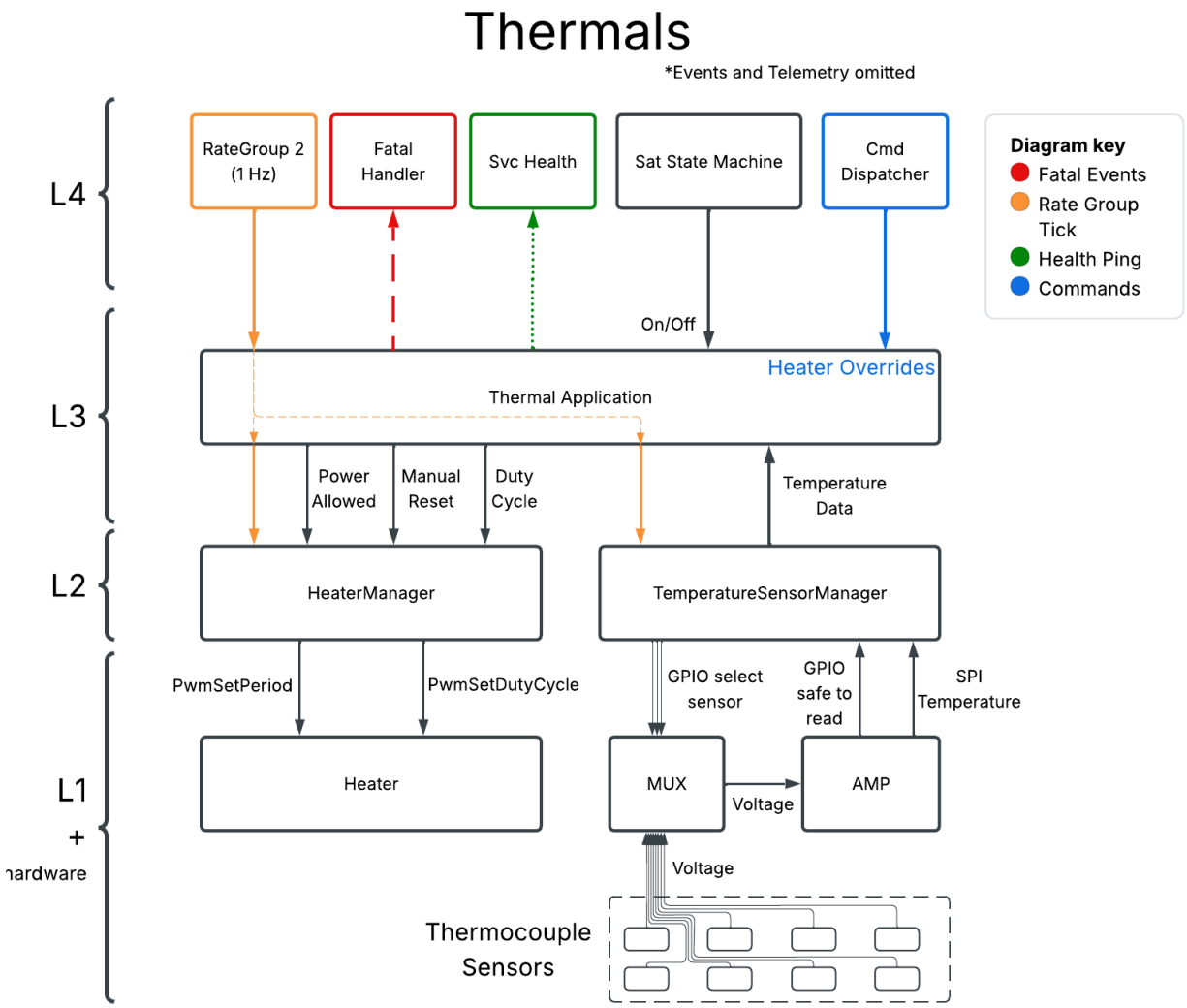


Figure 18. Thermal software topology

ThermalApplication coordinates HeaterManager and TemperatureSensorManager with the state machine, health, timing, and command services; the managers control heaters and read multiplexed thermocouple hardware.

5.5.4 - Interfaces and Integration

Interface	Implementation	Purpose
Thermocouples to multiplexer	Eight differential microvolt-level analog inputs	Component temperature measurements
CDH to multiplexer	Three GPIO address lines	Select one of eight sensors

Interface	Implementation	Purpose
MAX31856 to CDH	SPI Mode 0 up to 5 MHz plus active-low data-ready GPIO	Digitized temperature and sensor-fault data
CDH to heater	1-10 kHz PWM	Set battery-heater duty cycle
EPS to THR	12 V heater supply and 3.3 V sensing electronics	Thermal subsystem power

Thermocouple pairs route through the payload, ADCS, PDS, and BMS boards and the PC/104 connectors to the shared amplifier. Detailed attachment methods, wire routing, adhesive or epoxy selection, and thermal-contact conductance shall be closed through the thermal model, sensor-placement drawing, and qualification testing.

5.6 - Structures (STR)

The structure of HuskySat-2 is a 3U Cubesat frame (GranSystems), with dimensions 10x10x34 cm and a mass of approximately 0.580 kg. The structure is designed to house the payload hardware and all subsystems with PC-104 mounting holes for subsystem stacking, a dispenser deployment switch for post-launch activation, and an EGSE port for pre-launch work. It supports mechanical loads up to 30g vibration (see Structural analysis) and provides mounting interfaces for LOST and FOUND cameras, ADCS components, and EPS solar panels. The design allows for payload integration and maintains structural integrity during LEO operations, ensuring stable FOV alignment for FOUND (116.5 degree keepout cone) and LOST (45.5 degree keepout cone), critical for MO.1 and MO.2 validation.

5.6.1 - Structures Requirements

STR-1	All cameras shall have unobstructed views.
STR-2	The primary structure shall allocate 2 full 3U external faces of the satellite for the solar panels.
STR-3	The structure shall provide mounts for the ADCS subsystem.
STR-4	The structure shall provide mounts for the Payload subsystem.
STR-5	The structure shall provide mounts for the EPS subsystem.
STR-6	The structure shall provide mounts for the COMMS subsystem.
STR-7	The structure shall provide mounts for the CDH subsystem.

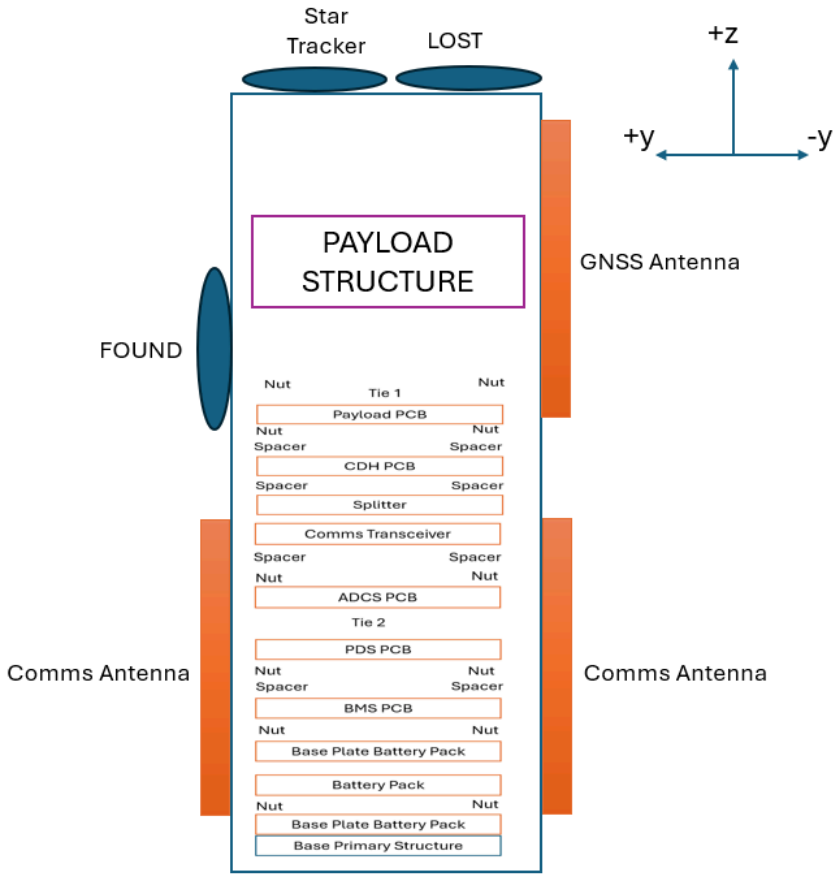
5.6.2 - Primary and Secondary Structure

The Gran Systems primary structure is an anodized 6061-T6 aluminum 3U frame with a 100 x 100 x 340 mm envelope, an average frame mass of approximately 580 g, and support for PCBs up to 95.9 x 95.9 mm. The primary frame also provides the dispenser-switch, remove-before-flight/inhibit, and EGSE-access interfaces used during launch integration and ground operations.

Four fully threaded M3x0.5 rods run through the secondary stack. Standoffs and nylon-insert locknuts establish the normal 15.24 mm board pitch. These nylon-insert locknuts provide compression preload and back-out resistance. The rail tips react against blind features at the primary-structure base. The battery pack is independently clamped between its base retention hardware and the approximately 4 mm spacer beneath BMS.

5.6.3 - Equipment Stack and Payload Mounting

The following schematic provides an overview of the order in which PCBs and other components are localized and mounted in the satellite. Solar panels are in +x and -x faces.



LOST and FOUND use XIMEA camera bodies secured to the lateral plates by mounting blocks and M2x0.4 camera fasteners. Split clamps retain the lens/baffle assemblies. The FOUND optical axis is nominally 90 degrees from LOST, with the final spacecraft face controlled by wiring and field-of-view closure. The Sagitta truth star tracker uses two bottom and two side brackets with M2.5x0.45 star-tracker fasteners and M3x0.5 plate fasteners. The IMMU also mounts to the interior face of a custom solar panel bracket.

5.6.4 - Interfaces and Integration

The EGSE port, present on the BMS board, allows for a power input and data transfer through an 8-pin connector. Aside from that, the STR electrical functions are passive: it provides equipment mounting, connector access, harness pass-throughs, chassis bonding, and common grounding paths. Mechanical integration must preserve optical fields of view, prevent connector interference, and permit repeated assembly and disassembly without degrading alignment or fastener retention.

6.0 Integration

These subsystems are integrated and managed by CDH, ensuring synchronized operation during the Experiment Phase. ADCS orients the satellite, CDH processes data, EPS powers operations, COMMS downlinks results, THR maintains thermal stability, and STR maintains structural integrity. This enables validation of LOSTs' 30 arcsec accuracy and FOUND's 10 km [TBR] position in LEO, paving the way for lunar applications in HuskySat-3 and beyond.

The integration process follows UNP-recommended assembly, integration, and test (AIT) practices, starting with subsystem-level verification before full system assembly. The process is led by the Testing and Integration Systems Engineer. Mechanical integration utilizes the PC104 stack within the 3U structure, with precision alignments for cameras verified using calibration fixtures and MGSE. Electrical integration involves harnessing connectors, ensuring fault-tolerant connections like reset lines and power rails without shorts or EMI issues. Software integration employs continuous integration practices for code commits, with pull requests (PR).

Testing builds complexity incrementally: subsystem tests precede functional tests, followed by environment tests. EGSE supports cabled RF and power simulations during integration, avoiding free radiation (UNP12-77). Cleanliness protocols (UNP 7.1) maintain controlled environments, with logging for access and procedures. This modular approach identifies integration issues early, updates ICDs, and ensures traceability to RVM.

7.0 Ground System

The ground system for HuskySat-2 ensures robust communication with the satellite, supporting command uplink, telemetry downlink, and data processing for LOST and FOUND experiments. It is verified to ensure LOST and FOUND validation.

7.1 - Communication Architecture

The HuskySat-2 ground communication architecture uses S-band at 2025-2110 MHz for uplink and 2200-2290 MHz for downlink. The spacecraft contains one EnduroSat transceiver connected through a hybrid coupler to two SANTV6 wideband patch antennas. The effective command uplink is 3.3 kbps. The transceiver's nominal 50 kbps downlink is reduced to 25 kbps effective throughput by forward-error-correction overhead. Downlink uses CCSDS TM framing and uplink uses CCSDS TC framing. The F Prime SDLS (using AES256 as the protocol) topology provides the flight-side security path; security associations, keys, ground interoperability, key-management procedures, and protection-failure handling remain [TBR].

7.2 - Ground Station Operations

The Husky Satellite Lab ground team, based at the University of Washington, handles daily mission operations, including Leaf Space pass scheduling, data validation, and fault detection. Automated scripts support pass prediction and health checks, but a valid flight contact is the beacon-response event reported by CommsApplication. Success metrics remain greater than 95% TBR command success and less than 1% TBR data loss.

GSTAT-1	The Ground Station shall support an effective telemetry receiving data rate of at least 25 kbps.
GSTAT-2	The Ground Station shall support an effective command uplinking data rate of at least 3.3 kbps.
GSTAT-3	The Ground Station shall receive data from Ground Command and Data Handling using a lossless data transfer method.
GSTAT-4	The Ground Station shall comply with all FCC regulations for operation with a frequency of under 10 GHz

7.3 - Hardware (GSTAT)

HuskySat-2 will use a ground station provided and operated by Leaf Space, as part of their managed Leaf Line network, rather than a self-built station. The station's hardware is owned and maintained by Leaf Space; HSL's role is to interface with it through their command-and-control systems. The functional signal path is as follows:

1. Rotator — structurally connected to the antenna. Rotates the antenna to point toward the satellite, receiving pointing commands from the command-and-control UI in GCDH.

2. Software Defined Radio (SDR) — converts the S-band signal to/from digital form. Receives commands from the GCDH Transmit Manager, which encrypts all uplink data (protocol TBD). Sends low-power S-band signals to the Power Amplifier. (Specific hardware TBD — confirming ground software architecture with Yehoushua; this may not be a HackRF given the antenna's performance specs.)
3. Power Amplifier — boosts the S-band signal for transmission.
4. Low Noise Amplifier (LNA) — amplifies received S-band signals while minimizing added noise, then passes the amplified signal to the SDR.
5. Antenna — a Leaf Space GAIA100 (3.7m) parabolic reflector, S/X switchable-and-simultaneous. Converts signals to/from RF waves and communicates directly with the satellite via S-band (uplink 2025–2110 MHz, downlink 2200–2290 MHz).
6. HSL does not select or configure this hardware directly; our involvement is limited to scheduling passes, sending commands through GCDH, and validating received data — Leaf Space manages the RF front end (rotator, amplifiers, SDR) as part of their service.
    a. Because we are using this provider, we will have to interface with them to obtain pass times and reserve/schedule when our satellite will do a ground station pass.

7.4 - Ground Software (GCDH)

The other half of the ground system at HSL is the Ground Command and Data Handling (GCDH) subsystem. It is responsible for storing and processing downlinked data and providing a user interface to send commands. It has the following requirements:

Number	Requirement
GCDH-1	The Ground Command and Data Handling system shall store a minimum of 7.5 GB of data.
GCDH-2	The Ground Command and Data Handling system shall have a user interface to input and send commands from the Command and Telemetry List (CTL).
GCDH-3	The Ground Command and Data Handling system shall provide visualizations of State of Health data from up to 48 [TBR] hours ago
GCDH-4	The Ground Command and Data Handling system shall process and send telemetry data to the science team.
GCDH-5	The Ground Command and Data Handling system shall be able to decrypt downlinked telemetry from the satellite.
GCDH-6	The Ground Command and Data Handling system shall be able to encrypt uplink commands.

The current software functions of the GCDH system includes the following:

1. Taking the protected CCSDS packets received from GSTAT, retaining packet order and raw-frame metadata, validating SDLS processing status, and producing raw telemetry and payload data for Yamcs, InfluxDB, Grafana, and science processing. The GCDH

implementation must interoperate with the selected F Prime SDLS (with AES256 encryption) configuration and preserve authentication or decryption failures for diagnosis.

2. Client API: Provides the interface between the ground software and client applications, handling external telemetry data requests and commands. We are using YAMCS as our primary mission control software to process telemetry and send commands. This telemetry will update in real-time when the satellite is doing a pass.
    a. The released Command and Telemetry List defines the available commands, arguments, packet formats, telemetry identifiers, and expected responses. The ground system shall form CCSDS commands and apply the approved SDLS protection before Leaf Space handoff; command acceptance, protection failure, spacecraft receipt, and command completion shall be recorded separately.
    b. Our YAMCS server will also provide an interface for event logging in the case that our satellite encountered a fault, so that the Grounds team can diagnose the issue.
    c. There will also be scripts and interfaces available to the Science team for evaluating the performance of LOST and FOUND as we receive experiment data throughout the mission.
3. Telemetry Visualization: Provides the interface to take the raw telemetry from our Mission Database (see below) and view graphs and information about the satellite. We are using Grafana as our telemetry visualization software.
4. Mission Database: Stores the shared command and telemetry structures used by the ground system and satellite. We are using InfluxDB as our backend database, which is shared by our mission control software (see above) and our telemetry visualization software (see below).
5. Satellite Location Propagator: Predicts future satellite locations using telemetry to support antenna pointing and ground-station communications.

The ground software and hardware interact as described in the block diagram below:

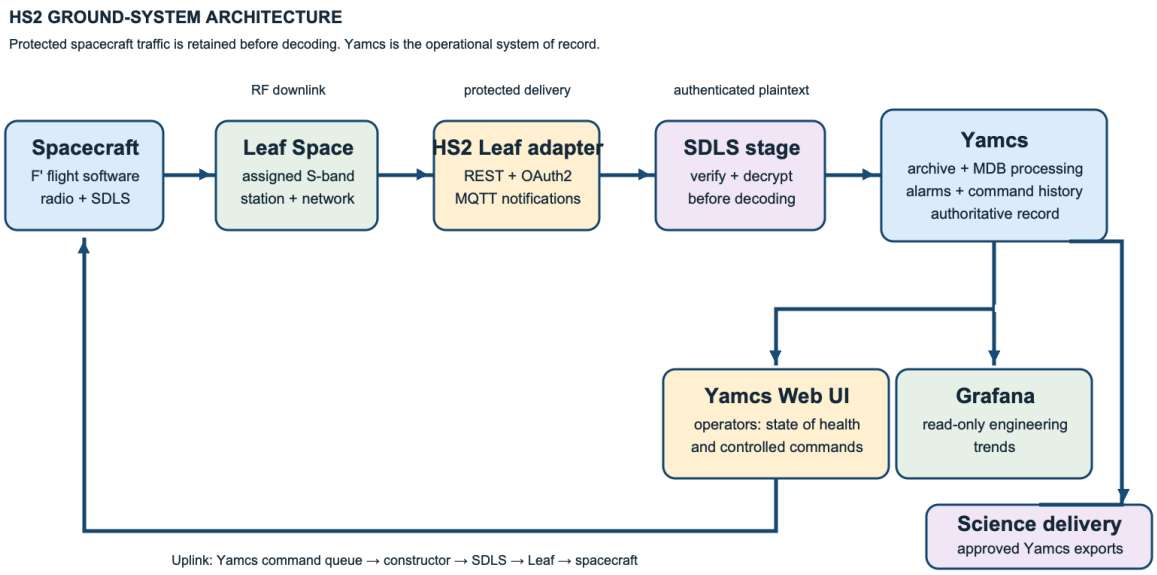


Figure 19. Ground Block Diagram

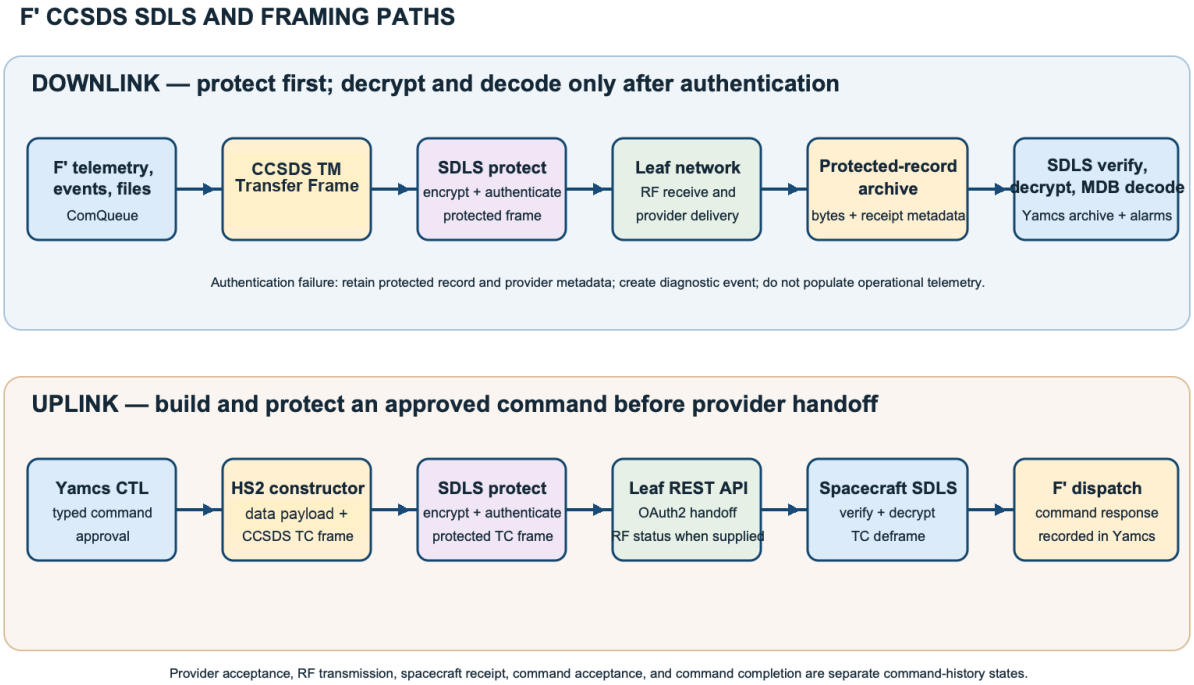


Figure 20. Pipeline of packetizing downlinked data and uplinking commands

7.5 - Ground CONOPS

HuskySat-2 uses the Leaf Space ground-station network for scheduled RF contacts and the HuskySat-2 Ground Command and Data Handling system for mission control, telemetry processing, and data archiving. Leaf Space performs the contracted ground-station contact and transfers contact records and spacecraft data to the HuskySat-2 ground system. The ground system preserves provider delivery records and protected spacecraft records, verifies and decrypts CCSDS SDLS traffic, validates released CCSDS packet formats, and archives decoded telemetry in Yamcs. Grafana provides engineering visualization from the Yamcs archive and does not provide command authority.

A nominal ground contact has four phases:

1. **Planning and readiness.** Before the pass, the operations team confirms the scheduled Leaf Space contact, assigned ground station, released flight-software version, released command and telemetry definitions, approved SDLS configuration, and command authorization. Commands remain queued until their approved release window.
2. **Acquisition and health assessment.** At acquisition of signal, the ground system records Leaf Space contact metadata and protected downlink records. Only SDLS-authenticated and format-valid telemetry enters operational processing. Yamcs decodes released state-of-health telemetry, including EPS/BMS, thermal, communications, and attitude data. Operators assess the spacecraft state against released flight rules and operational limits.
3. **Authorized command and payload operations.** Operators release commands only when command authority, spacecraft state, and applicable flight rules permit the action. The spacecraft downlinks payload products, including images, only when its released health and contact guards permit payload operations. The ground system archives associated attitude and quaternion telemetry with the payload data. Operators will authorize and schedule experiments by assigning both an ID and type, which the satellite will execute when it is able to enter its Science state.
4. **Post-pass reconciliation.** At loss of signal, operators verify pass status, command status, packet completeness, data gaps, duplicate records, authentication failures, alarms, and archive status. The ground system requests provider replay for expected data that is missing. Science processing consumes approved Yamcs exports and produces versioned data packages with provenance.

If RF acquisition fails, SDLS validation fails, telemetry indicates an out-of-limits condition, provider contact status is uncertain, or command completion cannot be verified, operators stop discretionary commanding and analyze the satellite state to attempt to recover.

This ground CONOPS supports MO-1 and MO-2 by preserving authenticated, time-correlated LOST and FOUND measurements, associated health telemetry, and operational context needed to calculate and report spread and bias.

8.0 Risk Management

Risks involve schedule, technical, and cost risks. The Husky Satellite Lab utilizes NASA Risk Management Strategies (NASA S3001), specifically the Risk Assessment Matrix (fig. 20):

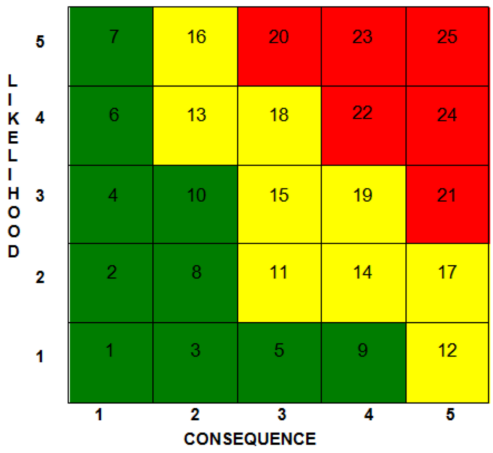


Figure 20. NASA Risk Assessment Matrix

Husky Satellite Lab's full risk management matrix is available below. This is written by the PM Team.

Table 20: HSL's full Risk Matrix

	Risk Statement	Consequence	Likelihood	Score
Scheduling				
	Given that COTS Star trackers have longer lead times, there is a possibility of a late arrival date adversely impacting the Payload subsystem, thereby leading to a delayed integration schedule.	4	3	19
	Given that a typical COTS Star Tracker far exceeds to allocated Truth Measure budget, there is a possibility of being unable to purchase a COTS Star Tracker by the end of Phase A adversely impacting the Payload subsystem, thereby leading to a delayed integration schedule.	4	4	22
	Given that Husky Satellite Lab's cleanroom isn't yet available for use, there is a possibility that students are prevented from beginning the satellite fabrication process adversely	2	1	3

	affecting HS-2 technical subsystems, thereby leading to a delayed fabrication and integration schedule.			
Cost				
	Given that an excessive number of solar cells are damaged during manufacturing and integration, there is a possibility of exceeding the allocated budget adversely impacting the Electrical Power System (EPS), thereby leading to budget reductions from other subsystems.	3	2	11
Technical				
	Given that the University of Washington has strict purchasing guidelines, there is a possibility of being unable to purchase satellite components efficiently adversely impacting all HS-2 technical subsystems, thereby leading to an incomplete engineering model by the end of Phase A.	4	3	19
	Given that undergraduate students make up Husky Satellite Lab, there is a possibility that students' experience and time management adversely affect the HS-2 team, thereby leading to an incomplete engineering model by the end of Phase A.	4	2	14
	Given that Husky Satellite Lab's cleanroom isn't yet available for use, there is a possibility that important satellite components arrive without cleanroom storage available adversely impacting HS-2 technical subsystems, thereby leading to damaged or malfunctioning satellite parts.	3	1	5
	Given that the final structural design has not been confirmed, there is a possibility of incomplete or inaccurate thermal modeling adversely impacting the Thermal subsystem, thereby leading to inadequate temperature	4	1	9

	control or failure to meet component operating temperatures.			
	Given that LOST and FOUND's requirements for output data aren't yet finalized, there is a possibility of selecting a camera that doesn't meet mission performance requirements adversely impacting the Payload subsystem, thereby leading to degraded image quality or inability to output necessary attitude/position data.	5	2	17

9.0 References

[1] Air University Press, “Technology Horizons,” [Online]. Available: https://www.airuniversity.af.edu/Portals/10/AUPress/Books/B_0126_TECHNOLOGYHORIZONS.PDF.

[2] “Assured Autonomy,” *Darpa.mil*, 2015. https://www.darpa.mil/research/programs/assured-autonomy.

[3] Vittorio Franzese, Pierluigi Di Lizia and Francesco Topputo. "Autonomous Optical Navigation for LUMIO Mission," AIAA 2018-1977. 2018 Space Flight Mechanics Meeting. January 2018.

[4] Curtis, H. (2024, January 19). *Earth sensors and horizon sensors*. Satsearch. https://blog.satsearch.co/2024-01-19-earth-sensors-and-horizon-sensors

[5] Nguyen, T. 2014. *Attitude determination using infrared Earth horizon sensors*. Small Satellite Conference. Retrieved from https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3096&context=smallsat

[6] Shimane, Y., Miraldo, P., Berntorp, K., Greiff, M., Elango, P., & Weiss, A. (2023, October 3). *High-fidelity simulation of horizon-based optical navigation with open-source software*. Mitsubishi Electric Research Laboratories. https://www.merl.com/publications/docs/TR2023-128.pdf

[7] Mortari, Daniele, et al. "Position Estimation Using picture Derivative." Aerospace, vol. 2, no. 2, 2015, pp. 214–243. Texas A&M University, College Station, Texas, and NASA Johnson Space Center, Houston, Texas. MDPI, https://sites.utexas.edu/renato/files/2017/04/Position-Estimation-using-picture-Dervatives.pdf.

[8] M. Polyakov, E. Zhang, K. Haining, "LOST: An Open-source Suite of Star Tracking Software," in Proceedings of the 37th Annual Small Satellite Conference, Logan, UT, USA, Aug. 2023, Utah State University. [Online]. Available: LOST: An Open-Source Suite of Star Tracking Softwar

[9] Redwire Space. “Tiny Star Trackers Help Spacecraft Find Their Place,” Redwire Space, Jacksonville, FL, USA, Apr. 5, 2019. [Online]. Available: https://redwirespace.com/news/tiny-star-trackers-help-spacecraft-find-their-place, Accessed: Sept. 26, 2025.

10.0 Revision Tracker/Change Log

#	Date	By	Change
1.0	3/1/25	Ellie Brosius	Creation of the Mission Design Document for SCR
2.0	3/25/25	Ellie Brosius	Creation of a separate file for the Mission Design Document for SRR
2.1	3/26/25	Yash Srivastava	Addition of Abbreviation Table and Change Log
2.2	3/29/25	Rassa Modares	Major Revision of Section 1.2: Military Relevance
2.3	4/10/25	Josh Lando	Rewrote Section 3.0 Experiment Plan
2.4	4/10/25	Ellie Brosius	Major Revision of Section 3.0 Experiment Plan
2.5	4/11/25	Josh Lando	Revision of section 2.2.1 update camera assumptions Revision of section 2.2.4 changed edge detection and edge location table Standardized paragraph spacing throughout document Fixed fig and table numbers Wrote section 2.2.2 Motivation for FOUND
3.0	5/11/25	Josh Lando	Table 13: typo
3.1	7/22/25	Cameron Lee	Implementing SRR Feedback, general typo/clarification
3.2	7/28/25	Josh Lando	Update section 2.0 with final FOUND implementation
3.3	7/30/25	Cameron Lee	Reorganized experiment plan section, included time stamp measurement
3.4	8/3/2025	Catherine Collison	Rewrote CONOPS, added diagrams for modes, states, and experiments.
4.1	8/6/2025	Josh Lando	Added back in section 2.2.4 Code Quality after deletion
4.2	9/17/25	Catherine Collison	Implemented PMR Feedback
4.3	9/25/25	Josh Lando	Fixed typos, made suggestions as the Science customer
5.1	9/28/25	Catherine	Rewrote CONOPS, moved sections around

		Collison	
5.2	9/29/25	Catherine Collison	Removed all mentions of separate payload computer
6	11/5/25	Catherine Collison	Implement PDR feedback
7	8/10/26	Addison Milne	Updated hardware lists and requirements for each subsystem
8	8/17/26	Addison Milne	Updated section 6 and section 1
9	9/1/26	Mahir Emran	Updated Satellite Bus section and CONOPS

Appendix

RVM: PDR RVM - Google Sheets

Link budget: OFFICIAL UNP BUDGETS - Google Sheets

Data budget: OFFICIAL UNP BUDGETS - Google Sheets

Mass budget: OFFICIAL UNP BUDGETS - Google Sheets

Volume budget: OFFICIAL UNP BUDGETS - Google Sheets

Power budget: OFFICIAL UNP BUDGETS - Google Sheets

Error budget: OFFICIAL UNP BUDGETS - Google Sheets

ARCI Management

The Husky Satellite Lab has adopted the ARCI management strategy to delegate tasks and deliverables throughout the UNP Program.

Definitions

- A - Accountable: The accountable individual ensures that all the responsible members complete the task. Accountabilities should not be delegated; it is best to assign the task to a single individual who can serve as the decision-maker and guide.

- R - Responsible: The responsible individual is delegated a responsibility from the accountable person and must complete that responsibility within agreed-upon parameters and an agreed-upon deadline. A task may have more than one responsible individual.

- C -Consulted: The consulted individual is the team's knowledge-holder. They're available for help, extra context, and advice on the task. Identify these people early on so you can incorporate them into the project and its workflow.

- I -Informed: The informed party is typically a stakeholder, leadership team, or approver who wants and needs information about the team's project. Ensuring there is an informed party promotes internal transparency, team alignment, and accurate project timelines.

HS-2 ARCI

Task	PM Team	Systems Team	Subsystem Leads	HSL Admin (Presidents)	Advisor
Communication with stakeholders	Accountable, Responsible	Informed		Informed	Informed
HS-2 Mission Vision	Responsible	Responsible		Accountable	Consulted
Internal Review Coordination	Responsible	Responsible, Accountable	Consulted		Consulted
Internal Documentation Management	Responsible, Accountable	Responsible	Responsible	Informed	
Programmatic Risk Management	Responsible, Accountable	Consulted	Consulted	Informed	Consulted
HS-2 Program Health Checks	Responsible	Informed		Consulted, Accountable	
UNP Deliverables	Accountable, Responsible	Responsible	Informed		Consulted
Technical Risk Management	Informed	Accountable, Responsible	Consulted		Consulted
Design Decisions	Consulted	Responsible, Accountable	Consulted		Consulted
UNP Feedback Implementation	Accountable, Responsible	Responsible	Responsible		Consulted