HuskySat-3: A Lunar Lava Tube Mapping CubeSat

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ABSTRACT

HuskySat-3 (HS-3) is a 12U CubeSat with the unprecedented objective of mapping subsurface lunar lava tube caves as long-term human habitation zones. HS-3 aims to self-dependently navigate and maneuver towards the moon from a Near-Rectilinear Halo Orbit (NRHO) and penetrate the lunar soil via an on-orbit Ground Penetrating Radar (GPR). To do this, HS-3 will house cutting edge CubeSat technology including a water-based bi-propellant propulsion engine, a Ka-band communication module, and a self-reliant optical navigation system, all of which are under development at the University of Washington's Husky Satellite Lab.

INTRODUCTION

In the previous few decades, the moon has continuously grown as a highly promising site for resource utilization as well as human and robotic exploration. Furthermore, evolving the lunar infrastructure and our knowledge of its extreme environment are critical steppingstones for future interplanetary travel to Mars and other celestial bodies. Even more so, technology advancements centered around lunar exploration can provide many applications for the improvement of Earth.

At the center of lunar exploration is the grand challenge of establishing infrastructures for long-term human habitation. A well-established human habitation site is an essential factor in the viability of future long-term and deep space human exploration. A major unknown in this field are the locations that could best serve as longlasting and safe habitation zones. Generally, there are three primary factors that greatly impact the feasibility of human habitation zones on the moon. One factor is the extreme ranges of the temperature on the lunar surface. Due to its slow rate of rotation, surface temperatures on the moon can range from less than a negative one hundred degrees to over one hundred degrees. Another important factor is prolonged exposure to radiation. The moon's lack of an atmosphere leaves the lunar surface vulnerable to solar radiation and cosmic rays for an extended period of time, adding significant risk to human life. Lastly, natural phenomenon such as meteorites is another significant factor in considering habitation zones. Once again, because of the lack of an atmosphere, surface level habitation zones are prone to catastrophic damages as a result of meteorite impacts. All of these issues prompt great concern in the viability and sustainability of long-term human habitation on the lunar surface and desperately require solutions.

The Husky Satellite Lab (HSL) at the University of Washington (UW) is investigating alternative regions of lunar habitation zones which exist underneath the lunar surface, namely, underground lava tube caves. Lava tubes are practically hollow tunnels a few hundred meters below the lunar surface. They are formed as a result of the flow of lava which eventually cools, hardens, and drains away. This process leaves an empty region underground with characteristics very similar to a cave. Throughout the past years, observations and models from the Lunar Reconnaissance Orbiter (LRO), the Kaguya Lunar Radar Sounder (LRS), and other gravitational modeling or observation spacecrafts have developed implications of the size and structure of these lava tubes. Thus far, the estimate and implications of lava tubes make them an incredibly strong candidate as locations for human habitation. Their predicted characteristics provide solutions to all the issues previously laid out. Thermal modeling of these subsurface structures as well as analogous comparisons to Earth lava tubes determine that their thermal environment is far more stable than the surface. More specifically, the minimum and maximum temperatures of these lava tubes only vary within a few tens of degrees Celsius. Moreover, the soil above the lava tubes inherently behaves as a shelter from radiation as well as meteorite impact. With these natural benefits, underground lava tube caves are manifested as a strong candidate for long-term human settlements.

Currently, although these subsurface caves are known to exist, there is very little insight into their internal characterizations, the overall quantity of the caves, as well as their specific locations. Thus far, all knowledge on these caves has been driven by estimates, models, and certain implications drawn from previous lunar missions. Hence, a subsurface map of the regions in which these caves are likely to form is a massive step forward to realizing the caves' potential for long-term human habitation. This is the scientific objective of HuskySat-3, a 12U lunar CubeSat under development at HSL. HuskySat-3 (HS-3) is the first of its kind, with one of the most ambitious scientific goals for a CubeSat to date.

HS-3 aims to maneuver and position itself in a circular low lunar orbit around the moon and map underground lava tubes caves with a Ground Penetrating Radar (GPR). HS-3's regions of interest are particularly the Oceanus Procellarum and Mare Imbrium regions of the moon, two of the largest smooth basaltic regions on the moon with the highest potential for lava tube development. To support this mission, HS-3 will include some of the most top-of-the-line CubeSat technologies. Hence, as a secondary objective, HS-3 is intended to behave as a technology demonstration satellite, pioneering a new era of CubeSat development and mission scope. The goal of this paper is to dive deep into the backend systems engineering of HS-3 and explore its feasibility.

ANALYSIS ARCHITECTURE

For rapid mathematical and system level analysis, a new workflow architecture was developed to increase organizational quality, maintain core mission objectives, and encourage heavy interdependencies throughout the team. An analysis architecture, referred to as "Analysis Cycles", was put together to implement this new workflow. This architecture consisted of three critical aspects of the analysis.

The first section of the analysis cycle was referred to as the cycle's "Entrance Criteria". In the first few cycles, the entrance criteria is composed of the overall mission statement, high-level mission objective, and a page of analysis assumptions. Once the fidelity and frequency of the analysis cycles increase, the entrance criteria of each cycle becomes filled with satellite and subsystem requirements, budgets, and operations, all of which would have been developed within the analysis cycles themselves. Furthermore, yet another and perhaps the most crucial information in the entrance criteria is the analysis parameters. The analysis parameters indicate what parameters will be analyzed in the current incoming cycle. The analysis parameters represent the priority of analysis and establish important thread connections between subsystem-to-subsystem relationships. When it comes to analysis priority and subsystem-to-subsystem relationships, within the representation of the analysis parameters also comes the notion of analysis "drivers". In other words, within the representation of analysis parameters, there are also indications of which parameters rely on other parameters, and hence, which parameters must be analyzed first. For instance, the central frequency and bandwidth of the satellite ground penetrating radar must be analyzed prior to its antenna and power analysis. This hierarchy of development leads to the program's ultimate source for scheduling priorities, namely, "critical path". The program's critical path is the combination of analysis that is *currently* driving the ultimate development of the satellite and its eventual launch. In other words, critical path deadlines are the deadlines that if pushed, would push the eventual development and launch of the satellite behind. Hence, critical path is the priority level of focus for the program's engineers. The entrance criteria in each analysis cycle is responsible for clarifying which parameters are driving analysis and which rely on the analysis results of other parameters. Therefore, in any analysis cycle, having a well thought through entrance criteria is essential to the cycle's success and contribution to the program.

The second section in an analysis cycle is the actual "analysis" section. This is where the magic happens! Once it's known what the parameters are that need analyzing, this is where all the math and physics takes place. The analysis section is a place filled with Matlab or Python scripts, Excel sheets, and diagrams. This is where new requirements, budgets, and operations get developed. For each piece of analysis, the set of underlying assumptions are marked in the entrance criteria. Given those assumptions, it's up to the engineers then to create the necessary analysis to come up with solutions required from the entrance criteria. Furthermore, all system and subsystem analysis that takes place must be made in an attempt to meet previously made and higher level satellite or subsystem requirements noted in the entrance criteria. For example, assuming the final orbital altitude and the initial launch state is known, and assuming an ideal 2D problem with disregards to the J2 effect, the team can develop requirements for delta-v performance for a supposed Hohmann transfer. Taking it an extra step further, if the mission has a total maneuver timeline allocated, the team can develop thrust and/or burn time requirements. While this is an example of a subsystem specific requirement, an example of a satellite or system based requirement can be the satellite's inclination. Again, let us create a situation where certain parameters have been developed in prior analysis cycles while others have been assumed. Let us say that the coverage zone for the ground penetrating radar has a minimum latitude of 60 degrees and the satellite requires a sun-synchronous orbit. From there, accounting for the J2 effect and a minimum inclination requirement of 60 degrees, it can be analyzed that the satellite shall be at a 87 degree inclination for optimal power generation and total surface area coverage. The documentation behind all of this analysis as well as the path forward to the next cycle is then put into the last section of the analysis cycle.

In the third and last section of the analysis, there is an exit criterion. The exit criteria must hold the newly made requirements from the analysis with all of the supporting mathematics. Ideally, every analysis parameter indicated in the entrance criteria has been analyzed and has now imposed new requirements on the satellite or its subsystem. These new requirements are stored in the exit criteria, which then become the entrance criteria for the next analysis cycle. Furthermore, the exit criteria also house the additions to any budgets or any new operations made. Lastly, lessons learned throughout the analysis process are documented in the exit criteria to improve the next cycle's efficiency and support the program's overall learning.

MISSION OBJECTIVES

The high-level mission objectives of this mission are driven by its impact and external uncontrollable parameters. At the core of this mission stands human habitation, for which safety is the number one priority. Hence, the first question to wonder about is which types of lava tube caves are the safest. The safety of a lava tube is driven by three major external uncontrollable factors: the tendency to collapse, radiation levels, and thermal state. The in-depth analysis of these parameters is outside of the purpose of this paper but the results and implications will nevertheless be discussed. Starting off with radiation, analysis must be conducted to find the necessary soil depth at which there is natural radiation shielding. In other words, analysis must show how deep into the soil does the radiation level become nominal. Based on radiation modeling and soil content through the depth of the moon, any depth lowering than roughly 10 meters is considered to yield nominal radiation levels. Going into thermal modeling, the same question must be asked as it was with radiation, namely, how deep into the soil do thermal environments and fluctuations become nominal and similar to what is experienced on Earth. By modeling thermal transfer through the lunar soil, rough estimates for thermal environments and fluctuations can be developed. Based on this analysis, depths any further down from 20 meters are considered to be thermally safe with fluctuations similar to those on Earth. Lastly, and perhaps most importantly is the consideration into how lava tube caves collapse. This analysis is dependent on a series of tensile loading resiliency models during moon-quake events. With this modeling, the ideal size ranges of the lava tube caves can be determined as well as any not-yet defined boundaries on depths. Based on this analysis, an ideal span range of 0.5 to 1.5km has been captured and the smallest lava tube diameter boundary is calculated as 15 meters. But, no additional constraints were set on the penetration depth. From these sets of analysis of these uncontrollable parameters, the complete constraint envelope has been developed for the onboard ground penetrating radar which will be discussed in the next section. Moreover, the last constraint needed are the regions of interest for the mission. For this, Mare Imbrium and Oceanus Procellarum were chosen as the best fits to the mission profile. Both these regions are considered to be a part of the Basaltic Maria regions on the moon which are the only regions where lava tubes can potentially form. In fact, Mare Imbrium and Oceanus Procellarum are the largest Basaltic Maria regions on the moon and compose nearly 20 percent of the moon's surface area. Additionally, what makes these regions even more so appealing is that their surfaces are some of the smoothest on the moon, making them ideal candidates for signal penetration and clarity. These pieces of information compose the high level mission objectives of the satellite and drive all system and subsystem analysis.

SPACECRAFT SUB-SYSTEMS

Based on the analysis conducted in the analysis cycles of this program, HS-3 will require several key subsystems to support its mission. As mentioned before, many of these subsystems have never been developed and tested in the scale and reliability required for HS-3. But, even though many of these subsystems require extensive levels of research and development, it's critical that the requirements developed for them are still mathematically feasible and viable. There are three primary ground breaking subsystems that HS-3 heavily relies on for the success of its mission.

One of these subsystems is HS-3's main propulsion module which is intended for orbital maneuvering. In its current state, HS-3 aims to launch into a Near Rectilinear Halo Orbit (NRHO) at the beginning of its mission. This orbit is chosen with several trade factors in mind but it is predominantly driven by future launch opportunities. NRHO is intended to be the future outpost orbit for the moon and eventually the location of NASA's Gateway station. Furthermore, the final required orbit for the satellite is driven by the ground penetrating radar's Signal to Noise Ratio (SNR) and Dynamic Range (DR). Overall, the basis of the mission's success relies on being close enough to the moon's surface so that the signal strength returning to the satellite can be processed and interpreted well enough to determine lava tube characterizations. This final orbit is defined as a circular orbit with an altitude of 50 kilometers. Fortunately, the mission's final and initial inclinations are the same which removes any need for spending propulsive elements on inclination change. Nevertheless, simple Hohmann transfer orbital mechanics math was conducted to find a rough estimate of the delta-v required from the satellite's propulsion system. Assuming a 2D problem, ignoring gravitational perturbations, and assuming perfectly spherical bodies, a rough delta-v of 880 m/s was determined for the main propulsion system onboard. Furthermore, based on the instantaneous requirements of the Hohmann transfer as well as an attempt to avoid prolonging the orbital transfer phase of the mission, a chemical combustion system is a natural choice for such a mission. That being said, there is very little heritage for CubeSat scale combustion propulsion systems, and no precedent whatsoever of those systems operating around the moon. Nevertheless, this kind of system is actively under development at the Husky Satellite Lab. Currently, the concept under development is a water based bi-propellant combustion system, famously referred to as an Electrolysis system. An Electrolysis propulsion unit operates by separating water into Hydrogen and Oxygen by running water through an electrolyzer. Once separated, the Oxygen and Hydrogen are kept in separate feeding systems and then mixed together, injected, and ignited to create a combustion reaction, and ultimately provide a large thrust burn (¿5N). Under analysis, it has been determined that the Electrolysis propulsion system has a 1000 m/s of delta-v potential, but the investigation and analysis of this determination is beyond the scope of this paper.

Another critical subsystem onboard HS-3 is its communication module. The choice behind the band of communication that HS-3 will be using is directly driven by the data rate it must support. The data rate itself is calculated based on a series of data analysis as well as assumptions about ground systems. The data rate that HS-3 must support is perhaps one of the most dynamic pieces of analysis of the mission, particularly because there are many different parameters that may impact it. That being said, HS-3's overall attitude towards first version of analysis is to assume worst case conditions. For communications, worst case conditions means assuming the satellite has very high amounts of stored data that must be down-linked and that communication time with the ground is extremely limited. The ground communication time aspect of this assumption is driven by commercially available methods of deep space communication. Well known candidates for this type of operation include the Deep Space Network (DSN) and the Near Space Network (NSN). The driving factor imposed by both of these options are the hourly costs of communication time. Both networks cost several thousands of dollars per hour for communication time. Furthermore, both networks maintain a very busy schedule that would be difficult to get into. Hence, HS-3's worst case condition assumes a total of 3 hours of downlink time with the ground. Going back to the total data that the satellite must transmit to Earth, there is yet another worst case condition that we impose on the spacecraft. Though the mission's goal is to map the Oceanus Procellarum and Mare Imbrium subsurface regions, the current analysis of the mission draws a bounding box over the entire area and assumes the system is collecting data throughout the entirety of passing the bounding region. This adds roughly 5 percent to the overall surface area coverage. Another worst case condition emerges from the frequency of observation. To enable data processing, add redundancy against failure, and improve the overall mission's reliability, it is assumed that each point on the region of interest will be scanned eight times. Once the surface area and amount of scanning was procured, a total data acquisition of roughly 90 Gigabytes was calculated, omitting all telemetry data and preput onboard memory. Once the total data and the amount of downlink time was known, a rough data rate of 5-10 Mbps was determined for the communication module. Achieving this data rate is by no means simple nor common. Hence, the communication module onboard HS-3 will be yet another moonshot of a system. To elaborate, HS-3 is currently pursuing a Ka-band communication system. This type of communication module is quite experimental on a CubeSat scale but preliminary analysis and design, the scope of which is beyond this paper, shows that it's mathematically feasible. The major challenges with the system arise from its large power consumption requirement (roughly 70-100 Watts) and deployment mechanism for its antenna which is currently designed to be about 0.2 meters tall.

Finally, the flagship payload and perhaps the most groundbreaking technology onboard is the Ground Penetrating Radar (GPR). This radar, in its required scale and operational range is completely unprecedented. The requirements for the GPR are directly driven by high-level mission objectives. More specifically, the size of the lava tubes of interest establish the necessary cross track and along track resolution of the radar, and the "safe" depth define the minimum penetration depth of the radar. Using values from the mission objectives, an ideal central frequency of 10MHz and a bandwidth of 8.75MHz can be obtained. But, continuing with more analysis cycles then sheds light on the very large antenna size required for low frequency radars. At 10MHz, the antenna length required would intuitively be considered too much of a challenge for a CubeSat. Hence, moving forward with a comprise, by increasing the central frequency, the antenna length could be shortened, but the penetration depth would also be closer to the surface. Through this trade, a compromise of 30MHz radar which would require two 2.5m dipole antennas while still meeting mission objective requirements was settled on. Currently, the biggest challenge remains in the Signal to Noise Ratio but more particularly in the Dynamic Range of the radar. To remedy these issues, processing techniques such as Synthetic Aperture Radar processing are being pursued and investigated.

Overall, very large challenges remain with the engineering of subsystems onboard HS-3. Nevertheless, large personnel and resources are being poured into the development and testing of these groundbreaking technologies to prove out concepts and build up system reliability.

MISSION OPERATIONS

Yet another important aspect of mission development comes from Mission Operations. While analysis cycles are terrific workflows for developing performance based requirements, mission operations have the power to impose functional requirements on the satellite and its subsystems. Currently, HS-3 seeks a robust autonomous system with redundant configurations that fall into the parameters derived through analysis cycles, acting as catalysts to the feasibility of the mission. HS-3's system operations concept is based on the following three principles expressed in order of importance:

1. Deploy and operate the spacecraft safely in the cislunar and lunar environments.

2. Acquire and disseminate spacecraft telemetry, Ground Penetrating Radar (GPR) instrument data, and mapping products to meet mission requirements.

3. Operate as efficiently as possible, optimizing the cost and resource usage while meeting data availability and latency requirements.

These principles comprise the foundation of the operational system. Each facet of HS-3's mission operations will address these priorities.

As it stands, with the concept of worst case conditions in mind, HS-3 targets a fully autonomous configuration for all operational stages to manage the complexities of deep space maneuvers and the inherent limitations of long-range communication. This architectural choice allows the satellite to prioritize communication link budgets for high-bandwidth science operations and the transmission of critical lunar subsurface data.

Despite this targeted autonomous capability, the system design includes dedicated provisions for manual command intervention. This capability is maintained as a critical redundancy to allow the ground segment to issue direct commands in the event of unforeseen environmental anomalies, Tier 3 fault triggers, or scenarios where the onboard autonomous logic requires manual reconfiguration to ensure the continued safety and success of the mission. Consistent with industry best practices for high-reliability systems, manual overrides permit direct engineer control over all mission-critical functions.

To streamline operations and reduce redundancy, HS-3 employs a strictly segmented, three-tiered fault management architecture. This architecture is defined as the following:

- **Tier 1 (Transparent/Local):** Faults handled automatically by redundant systems. These do not disrupt the main operations flow and are resolved transparently to the primary operational sequence. These do not appear in the operations flow but are contextualized in redundant system descriptions.

- **Tier 2 (Operational Shift):** Anomalies requiring an active change or branch in operations (e.g., executing a correction burn, adjusting a timeline). These are mapped in the main operations sections.
- **Tier 3 (Mission Stop / Safe Mode):** Critical failures (e.g., low battery, lost attitude/state, stuck thruster, or persistent unresolvable faults) that immediately halt current operations and trigger an autonomous Safe Mode.

It is critical to distinguish between mission phases and operational modes. Phases represent the chronological progression of the mission timeline from launch to decommissioning. Modes (or State) define the specific hardware and software configurations the spacecraft assumes to execute the requirements of any given phase.

- **Pre-Launch:** The pre-launch phase encompasses all activities from system assembly through integration into the launch vehicle/bus. This includes ground system testing, flight-to-ground end-to-end testing, and validation of the autonomous flight software.
- **Deployment and Initial Acquisition:** This phase begins upon separation from the launch vehicle into a Near-Rectilinear Halo Orbit (NRHO). It includes the automatic boot sequence, initial detumble, deployment of the solar array, and the acquisition of the first stable communication link with the ground segment.
- **Transfer Phase:** The Transfer Phase maneuvers the 12U CubeSat from NRHO into the target circular Low Lunar Orbit (LLO). It is divided into two primary autonomous campaigns: Phase 1 (lowering the apoapsis via retrograde burns at periapsis) and Phase 2 (lowering the periapsis via retrograde burns at the new Phase 1 apoapsis).
- **Science Operations (LLO):** Upon arriving in LLO, the primary science mission begins. HS-3 will continuously orbit and map the subsurface features of the Oceanus Procellarum and Mare Imbrium regions. During this phase, operations cycle heavily between data collection over the target regions and high-bandwidth data downlink via the RF communications system.
- **End-of-Mission Decommissioning:** Upon completion of the primary mapping objectives or depletion of the combustion propulsion reserves, the mission transitions to the decommissioning phase. To prevent orbit debris in LLO, HS-3 will perform a final series of maneuvers resulting in a targeted, controlled crash into the lunar surface, avoiding any historical landing sites.

The HS-3 state hierarchy is designed to support the autonomous design philosophy, switching between states based on orbital position, scheduled events, and fault triggers.

- **Coasting / Stationkeeping Mode:** This is the default baseline state of the spacecraft during non-critical trajectory segments. The spacecraft maintains a power-positive, sun-pointing attitude. The Optical Navigation system takes periodic updates to reduce covariance, and the flight software runs continuous Tier 1 fault monitoring. The GPR and main propulsion systems are powered down and passively thermally stabilized.
- **Propulsive Maneuver Mode:** Entered exclusively during the Transfer Phase or for LLO orbital corrections. In this state, the spacecraft aligns its attitude for a tangent retrograde (or prograde) burn. High-frequency time tracking, IMU rate monitoring, and autonomous abort thresholds (Tier 2/3 triggers) are active. Combustion valves are armed, and the Optical Navigation system may be used for immediate post-burn state vector updates.
- **Science Observation Mode:** Activated only when passing over the regions of interest (ROI). The ROI is defined as a rectangular region bound by the largest and smallest longitudes and latitudes of the target regions (Oceanus Procellarum and Mare Imbrium). The spacecraft assumes an Earth/Moon nadir-pointing attitude. The GPR is fully powered and actively collecting subsurface sounding data. To ensure data redundancy, the system is designed to complete 8 full passes over the ROI before transitioning to a processing or downlink state.
- **Data Processing and Communications Mode:** Because power and thermal constraints limit simultaneous operation of the GPR and RF communications, this mode is entered after the completion of the 8-pass Science Observation cycle. The GPR is powered down to meet the 145 W power requirement of the communication system. The total estimated data volume of 715.2 Gb requires approximately 14 orbits for full transmission. The spacecraft aligns its RF optics with the designated ground station or lunar relay to downlink the Compiled Data Package.

  NOTE: *This may be amended to contain intermittent processing and communications, in order to increase likelihood of successful and robust data.*
- **Safe Mode (Tier 3 Fault State):** Triggered automatically by the Tier 3 fault management system in response to critical failures (e.g., severe battery depletion, loss of attitude knowledge, or stuck thruster valves). In Safe Mode, all non-essential systems (including payloads and propulsion) are immediately powered down. The spacecraft assumes a passively

stable, sun-pointing attitude to maximize solar power generation and waits for ground station intervention via the backup RF command link.

This operational philosophy and current organization is the initial backbone of HS-3 but the in-depth details of each modes and the satellite's state machine are beyond the scope of this paper. The level of operational complexity for HS-3 is yet another aspect of its ambition and ground breaking stance. Autonomous flight software, controls, data and signal processing, and more are all under development at HS-3.

FUTURE WORK AND CONCLUSION

Currently, the first version of the mission has been developed. This back end mission development, however, has been completely rooted in mathematics and physics. Now is the time to begin the engineering. While requirements have been thoroughly developed, designs are still very much a work in progress. To catalyze development and boost organizational efforts, "Design Cycles" will be built and implemented into the program. The overarching notion of these cycles are very similar to the analysis cycles only with different information being put inside of them. Furthermore, the program is now growing and engineering rigor is becoming increasingly important. At a program like this, top-of-the line and constant communication is an essential part of success, as well as the team's ability to go above and beyond their roles.

Furthermore, to add on support to the development of the GPR, a university-based capstone class team is developing a first version prototype of the radar with direct mentorship from the Jet Propulsion Laboratory (JPL) and university faculty. In further support of this project, a JPL systems management and validation software called Aerie has been built, hosted, and developed for the Husky Satellite Lab's usage. Additionally, a systems requirements management tool has been procured from a startup company, Stell Engineering, which is used to document and track requirement development, rationale, status, ownership, verification methods, and more. HS-3 is consistently searching for more partners, mentors, and stakeholders to join them on this incredible journey towards the unknown.

HS-3, even with all of its challenges, stands as one of the greatest undertakings in CubeSat history and will be a revolutionizing satellite once it succeeds. The Husky Satellite Lab, overfilled with passion and a fiery drive for innovation is "over the moon" to be a part of such extraordinary times and to contribute to humanity's future in space.