THE PENNSYLVANIA STATE UNIVERSITY

2018 AIAA STUDENT DESIGN COMPETITION

Mission MoonCubed

Robotic Lunar Crater Resource Prospecting

The Flat Moon Society

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Final Report

April 23, 2018

Executive Summary

As part of the 2018 AIAA Student Design Competition, the Flat Moon Society will send a group of small robotic vehicles to the surface of the Moon with a primary mission objective of determining the locations and quantities of water deposits in two lunar craters. Secondary mission objectives include determining concentrations of other elements within a crater and preforming future observations and communications with the Mothership after the primary mission has ended. Mission MoonCubed hopes to provide information necessary for developing habitats and launch capabilities on the Moon, aiding humanities efforts to become a multiplanetary species.

The functional requirements for Mission MoonCubed define how well the system must perform to meet its objectives. Each MoonCube is equipped with a spectrometer capable of detecting water traces as little as 1% in regolith. Additionally, a ground penetrating radar on-board the MoonCubes allows for water detection up to a depth of 10 meters. To ensure that all primary mission data collected by each rover is successfully transmitted, the MoonCubes will complete all primary data transmissions before 10% remaining battery life.

The operational requirements for Mission MoonCubed determine how the system operates and how users interact with it to meet their specific needs. The expendable and autonomous MoonCubes for the mission are battery powered and have an expected lifetime of three days. The MoonCubes and LunarBuses are specially designed to survive harsh lunar conditions. The Mothership is designed to survive for at least three years in lunar orbit to enable secondary missions.

The constraints for Mission MoonCubed define and limit the cost, schedule, and implementation techniques available for reaching the objectives. For this mission, constraints were set by the 2018 AIAA Student Design Competition for Robotic Crater Resource Prospecting. These constraints state that the cost of the mission should not exceed $500 million USD (FY17) and that the mission should complete its primary objective no later than December 31, 2024.

The engineers of Mission MoonCubed have carefully designed the mission to satisfy the requirements and constraints. The use of 150 distributed MoonCubes and three LunarBusses per crater greatly increases the possible coverage and chance of success of the mission while reducing single points of failure. The cheap and expendable MoonCubes also reduce the total payload mass of the

mission and greatly reduce the total cost.

The mission will consist of the following three primary phases: (1) Transport (2) Deployment (3) Operation. Phase (1) - the transport phase - includes launch from Cape Canaveral and orbital trajectories and maneuvers from low Earth orbit (LEO) to trans-lunar injection orbit, followed by insertion into lunar orbit. Phase (2) - the deployment phase - involves the deployment of the LunarBuses and MoonCubes. Phase (3) - the operational phase - will begin once the MoonCubes have been deployed in the Shackleton and Cabeus craters and will last until the end of their operational periods. This sequence of events is represented in Figure 1.

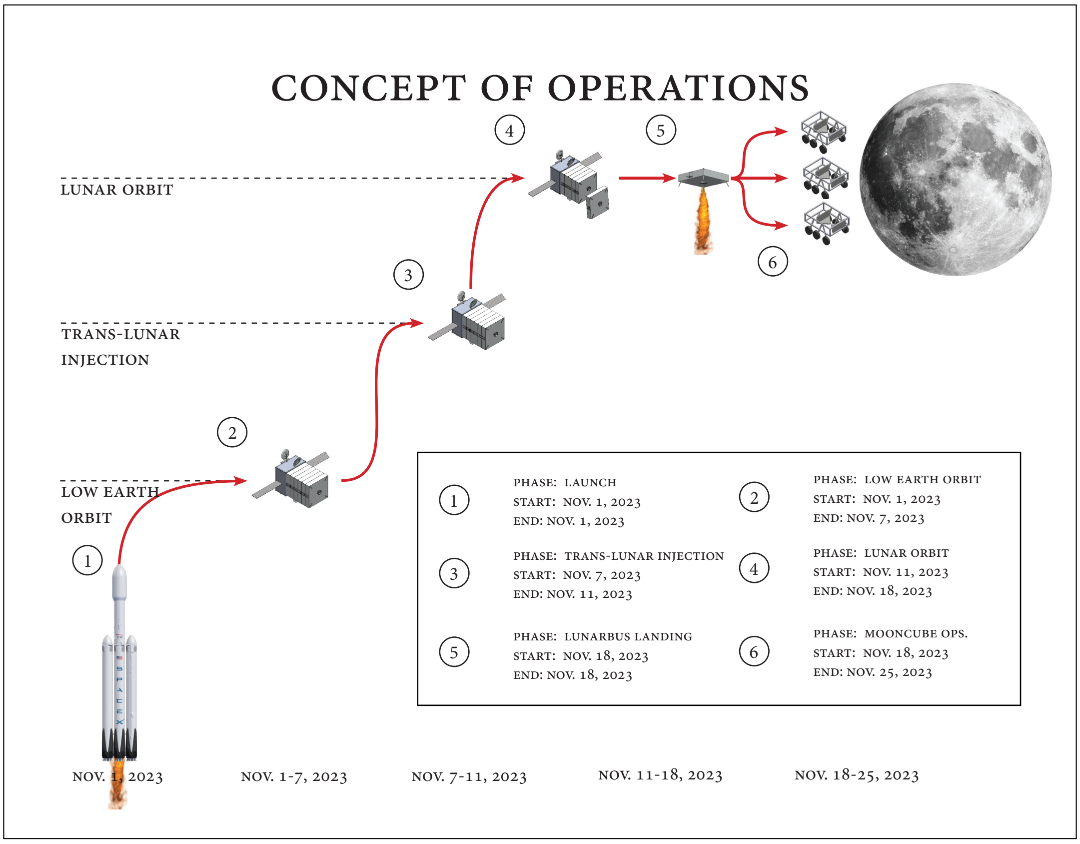

Figure 1: High-level mission overview

Preliminary calculations for total payload mass, cost, and power act as verification to show whether or not Mission MoonCubed is on track to meet the mission constraints and requirements. The total payload mass for the mission is 30,390 kg. The total cost of the mission is $475 million.

The total power requirements for the Mothership, LunarBuses, and MoonCubes are 360 W, 400 W, and 125 W, respectively. All calculations are estimated to be within a 25% margin.

The Structures and Mechanisms subsystem of Mission MoonCubed is responsible for the structural design of all vehicles as well as mechanisms used in this mission, such as the MoonCube deployment system. The Mothership is an aluminum and AS4 carbon fiber structure with dimensions of 4 x 4 x 2 meters. Six LunarBuses are stacked and attached to the body of the Mothership. Each LunarBus is an aluminum structure with dimensions of 3 x 3 x 0.75 meters. Contained within each LunarBus are 50 MoonCubes. The MoonCubes have an aluminum body with dimensions of 0.4 x 0.3 x 0.1 meters. During LunarBus decent, a side-mounted ground penetrating radar will deploy using a spring system. Before landing, four legs made of carbon composite AS4 and shock absorbing springs and dampers will extend outward. Once the LunarBus has landed, the bottom plate of the vehicle will drop to the Moon's surface, bringing along the MoonCubes. The MoonCubes will drive off of the lowered platform and begin prospecting the Moon.

The payload for Mission MoonCube will be carried to low earth orbit from Cape Canaveral on a Falcon Heavy rocket. The Falcon Heavy has a payload capacity of 64,800 kg to low earth orbit, which is within the expected payload mass of 30,390 kg. Additionally, the fairing of the Falcon Heavy rocket has an internal height of 13.1 meters and a diameter of 5.2 meters. Our payload has height of 8.5 meters and a diameter of 4 meters. The cost of a Falcon Heavy rocket is the cheapest available for the mission at $90 million in 2018, which is only 18% of the total budget. As of April 20, 2018 the Falcon 9 rocket has completed 51 of 53 primary missions.

The Mothership orbiter will utilize a hypergolic propulsion system consisting of 16 Moog 5 pound-force ACS thrusters for orbital maintenance and attitude control. It will use a gimballed Aerojet AJ10-190 for orbit transfer from LEO to lunar orbit capable of producing 40 kN of thrust and producing a ΔV of 3.13 km/s for trans-lunar injection and 0.82 km/s for insertion into lunar orbit. The LunarBus propulsion system consists of a gimballed main AJ0-190 engine and 8 Moog 5 pound-force ACS thrusters. Once located above the crater while in lunar orbit, the LunarBuses will release sequentially from the Mothership and perform three burns during descent with a total ΔV of 778 m/s. The 8 ACS thrusters will be used to control landing trajectory and orientate the LunarBus during the descent phase. All propulsion systems will utilize hypergolic propellant consisting of monomethylhydrazine (MMH) and mixed oxides of nitrogen (MON). The Mothership and LunarBuses will contain two evenly distributed MMH and MON tanks for redundancy and will be pressurized by single helium tank.

The ground control system of Mission MoonCubed is responsible for collecting and processing data transmitted from the Mothership as well as sending instructions to the spacecraft. Ground control operations for Mission MoonCubed will be performed in Pasadena at the Jet Propulsion Laboratory's ground control station. Our ground control system will utilize the Near Earth Network to provide telemetry, commanding, and ground-based tracking to the Mothership.

The communication subsystem of Mission MoonCubed is divided into three distinct areas: (1) surface to surface, (2) surface to lunar orbit, and (3) lunar orbit to Earth. Only Ultra High Frequency (UHF) and S-band communication systems will be used. The UHF-band will be used to provide communications between the Mothership, LunarBuses, and the MoonCubes. The S-band will be used to provide communications between lunar orbit and the Near Earth Network (NEN). NEN allows for nearly uninterrupted S-band data links in lunar orbit.

The guidance, navigation, and control system includes the positioning, attitude, and orbital determination for the mission. The Mothership will use two star trackers, two sun sensor, and two inertial measurement units (IMU) for navigation in trans-lunar injection (TLI), orbital maintenance, and attitude control. Each LunarBus will implement a three-axis control using two star trackers, a laser altimeter, and two IMUs to determine attitude adjustments and thrust output to achieve level landing and an impact velocity under 1 m/s. The MoonCubes will function using swarm technology in order to increase possible coverage within a crater. Each of the MoonCubes will use an IMU and transponder communicating with its respective LunarBus to determine position. Upon successful discovery of water using GPR, the MoonCube will deploy a drill and laser spectrometer to analyze the sample. They will relay sample data and position back to the central LunarBus to provide a real-time map of all other MoonCubes.

The guidance, navigation, and control system for Mission MoonCubed includes orbital maintenance and attitude control of the Mothership, descent and attitude control of the LunarBus, and navigation of MoonCube rovers on the lunar surface. The Mothership will use two star trackers, a sun sensor, and an inertial measurement unit (IMU) for attitude determination. Each LunarBus will implement three-axis control using two star trackers, a laser altimeter, and an IMU. The MoonCubes will function using swarm technology in order to increase possible coverage within a crater. Each of the MoonCubes will use an IMU and transponder to communicate with the LunarBus to determine position and relay data in order to provide a real-time map of all other MoonCubes as well as their findings of water.

The Mothership, LunarBuses, and MoonCubes each have their own individual power systems for Mission MoonCubed. The Mothership will be powered by solar arrays and a space rated battery bank for power when shaded from the sun. LunarBuses will be equipped with high energy density hydrogen-peroxide-based fuel cells to allow for constant data processing and transmission. MoonCubes will, also, be powered by hydrogen-peroxide-based fuel cells due to their high in-class energy density of 2700 Watt-hours per kilogram and their ability to operate at temperatures as low as -40° C.

The thermal subsystem works to ensure that all parts within the Mothership, LunarBuses, and MoonCubes are at appropriate temperatures. Direct exposure to solar radiation causes rapid heating, while any surface not exposed loses heat at a similar rate. Therefore, the Mothership will be equipped with heat pipes, louvers, and electric heaters to maintain an adequate operating temperature. The thermal control system for both MoonCubes and LunarBuses will be operating in lunar craters with temperatures as low as -238° C. Heatpipes, electric heaters, waste heat from the hydrogen fuel cells, and louvers will maintain a LunarBus internal temperature between 150° C and 200° C. MoonCubes will use electric heaters and aluminized mylar thermal blankets to maintain operating temperatures of 0° C.

The payload subsystem consists of a swarm of rovers called MoonCubes. These small rovers provide an efficient and cost effective way to rapidly prospect lunar craters. Due to the depth, temperature, permanent shadow from the sun, traditional rover designs would not be effective. The large number of MoonCubes increases the success rate by offering redundancy if some of the vehicles fail. The MoonCubes are equipped with a ground penetrating radar system as well as a lunar camera, laser spectrometer, and drill to assist in prospecting materials near the lunar surface. The LunarBuses have a side-mounted ground penetrating radar to select an appropriate landing location during descent.

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Nomenclature

C&DH	Command and Data Handling
COTS	Commercial Off The Shelf
DHANS	Deployable Helical high-gain Antenna for Nano-Satellites
GCS	Ground Control System
GNC	Guidance, Navigation, and Control
GPR	Ground Penetrating Radar
JANAF	Joint Army Navy NASA Air Force
kbit/s	Kilobit per second
LCLD	Lunar Camera, Laser spectrometer, and Drill
LCROSS	Lunar Crater Observation and Sensing Satellite
LEN	Lunar Exploration Network
LEO	Low Earth Orbit
LRO	Lunar Reconnaissance Orbiter
LunarBus	The spacecraft that will be used transport the MoonCubes from the Mothership to the lunar craters, houses MoonCubes
MER	Mars Exploration Rover
MHz	Megahertz
MIPS	Million Instructions Per Second
MMH	Monomethylhydrazine
MON	Mixed Oxides of Nitrogen
MoonCube	Small autonomous vehicle that will prospect lunar craters for water deposits
Mothership	The satellite in lunar orbit, houses LunarBuses
NEN	Near Earth Network
RAM	Random-Access Memory
RIMFAX	Radar Imager for Mars Subsurface Experiment

S&M	Structures and Mechanisms
SMR	Side-Mounted ground penetrating Radar
SSR	Solid State Recorder
TCS	Thermal Control System
TDRS	Tracking and Data Relay Satellite
UHF	Ultra High Frequency
U	10 x 10 x 10 cm
VMC	Vehicle Management Computer

1 Introduction

Space is a vastly unexplored frontier. Over time, the buildup of technology has allowed humankind to venture further and further into previously unexplored areas of space around Earth. Uncrewed spacecraft have visited all of the planets in the solar system, as well as certain planetary moons, asteroids, and comets. Crewed missions, however, have only transported humans to the Moon during the Apollo era in the late 1960s to early 1970s. This is primarily due to the inhospitable environment in space as well as the difficulties involved with transporting and establishing necessary resources to support human life. Out of all the resources required to support crewed exploration missions, the most coveted is water.

Establishment of a water resource system in cis-lunar space will greatly enable future exploration missions throughout the solar system. For crewed missions, water is the cornerstone of the environmental control and life support systems. In addition, water can be broken down into hydrogen and oxygen molecules and then used for propulsion systems. This makes the Moon an excellent potential location for in-situ resource collection to support future exploration missions. Several lunar probes have shown evidence of water on the lunar surface. The highest concentration of water is likely to be in the polar regions and in deep impact craters, regions that have been protected from solar heating which would otherwise vaporize the water. As part of the 2018 AIAA Student Design Competition, the Flat Moon Society will send a group of small robotic vehicles to the surface of the Moon with a primary mission objective of determining the locations and quantities of water deposits in two lunar craters. Secondary mission objectives include prospecting for other resources and mapping of visited craters.

Mission MoonCubed begins with a launch from Cape Canaveral aboard a Falcon Heavy rocket to LEO, followed by a series of orbital maneuvers using the propulsion system aboard the Mothership in order to achieve a lunar orbit. Once in the appropriate lunar orbit, six LunarBuses will depart from the Mothership, each on their own predetermined path to a lunar crater where they will land and deploy a group of 50 MoonCubes. Upon deployment, the MoonCubes will begin operation and work collaboratively to determine the locations and quantities of water on and near the surface of each crater. Each MoonCube is equipped with its own collection, sensing, and scientific instruments, which enable secondary mission objectives and greatly increase the possible coverage and quantification of water deposits around each crater landing location. Up until the end of their operational lives, the MoonCubes will communicate valuable data collection information with one another and transmit data to the LunarBus; the transport vehicle that now acts as a data storage and communication center used to transmit MoonCube data to the Mothership, then from the Mothership to Earth.

2 Mission Constraints & Requirements

In order to ensure that the mission objectives are met within the cost, design, and schedule constraints as listed by the 2018 AIAA Student Design Competition, requirements and constraints for all aspects of the mission have been carefully determined as shown in Table 1. These requirements and constraints serve as quantitative expressions of how well the mission objectives are achieved while meeting the constraints and requirements for this mission.

Table 1: Mission Constraints and Requirements

Functional Requirements	
Performance	Detect water on the lunar surface & up to a depth of 10 meters
Coverage	Data collection & sampling covering at least 600 square kilometers of the surface per crater, total of two craters
Interpretation	Accurate identification of water for samples containing at minimum 1% water
Timeliness	Complete transmission of data from MoonCubes by 10% remaining battery life
Secondary Missions	Prospecting for other resources, future plans for the Mothership
Operational Requirements	
Commanding	Semi-commandable Mothership & LunarBus, fully autonomous and collaborative MoonCubes

Table 1: Continued

Mission Design Life	Mothership life of 3 years MoonCube battery life of at least 72 hrs LunarBus life of 7 days
System Availability	100% availability during mission life
Survivability	Lunar orbit, lunar surface in sunlight and darkness, radiation hardened data storages
Data Distribution	LunarBus capable of receiving data from all MoonCubes simultaneously while transmitting data to Mothership, MoonCube communications
Data Content, Form, and Format	Raw data, telemetry

Constraints	
Cost	$500 million USD (FY17)
Schedule	Mission completion before 31 Dec. 2024
Risk	Probability of success > 90%
Regulations	Orbital & lunar debris
Development Constraints	AIAA competition requirements

2.1 Functional Requirements

The functional requirements that have been determined for Mission MoonCubed define how well the system must perform to meet its objectives. The primary mission objective of finding the locations and quantities of water is quite clear, yet there is significant uncertainty with where the water deposits may be and what tools and devices would be best for detecting and quantifying them. As a result, the mission design and functional requirements have been carefully selected in order to maximize the probability of a successful mission by implementing a variety of data collection methods and tools.

The mission involves the use of a large number of smaller lunar rovers - called MoonCubes - each equipped with their own set of data collection instruments. This greatly increases the possible overall performance and total coverage for the mission, and enables secondary objectives such as detecting other materials. For example, spectrometers on-board the MoonCubes specialize in detecting traces of water as low as 1% near the surface using neutron spectroscopy, while a ground penetrating radar system detects water under the surface up to a depth of 10 meters. Using a large number of smaller rovers and multiple LunarBuses per crater also allows for greater total sampling coverage within a crater. It is estimated that the MoonCubes will be able to cover an area of 600 square kilometers during the duration of the mission. This calculation was estimated by multiplying the average speed of the MoonCube vehicle (0.25 kilometers per hour) by their estimated operational period of three days. To ensure that all primary mission data collected by each rover is successfully transmitted, the MoonCubes should complete all primary data transmissions before 10% remaining battery life.

2.2 Operational Requirements

The operational requirements for Mission MoonCubed determine how the system operates and how users interact with it to meet their specific needs. This mission is solely scientific and will only be interacted with by trained operators when necessary. The mission is designed to be completely autonomous due to the fact that certain vehicles and rovers will be in locations unable to communicate directly with ground control; however the Mothership and LunarBuses have been designed to be semi-commandable if necessary. During the operation phase, all of the MoonCubes will be in constant communication with each other; each LunarBus will serve as the central communication hub between the MoonCubes and the Mothership.

The expendable MoonCubes for the mission are battery powered and thus have a relatively short lifetime of 3 days. The LunarBuses have the longest operational lives (excluding the Mothership) of 7 days to ensure that all necessary raw and telemetry data can be transmitted to the Mothership. The MoonCubes and LunarBuses are designed to operate on the lunar surface in sunlight and darkness for their respective operational periods. The Mothership is designed to survive for at least three years in lunar orbit to enable secondary missions.

2.3 Constraints

The constraints for Mission MoonCubed define and limit the cost, schedule, and implementation techniques available for reaching the objectives. For this mission, some constraints were set by the

2018 AIAA Student Design Competition for Robotic Crater Resource Prospecting. These constraints state that the cost of the mission should not exceed $500 million USD (FY17, including launch vehicles) and that the mission should complete its primary scientific mission no later than December 31, 2024. Regulations involving orbital and lunar debris will be considered for the shutdown of the lunar vehicles and orbiter. For Mission MoonCubed, the probability of success is estimated to be greater than 90%. This probability was estimated by implementing qualitative risk assessments of the mission, as well as by implementing redundant features and avoiding single points of failure.

3 Concept of Operations

3.1 Mission Objectives

The primary objective of Mission MoonCubed involves sending groups of autonomous, robotic vehicles to the surface of the Moon in order to determine the locations and quantities of water deposits in two lunar craters. The design of the mission has been well thought out in order to meet the specified mission requirements and constraints. Specifically, the mission design provides exceptional performance and coverage at relatively low cost and risk.

Instead of sending a single, large multi-purpose rover to the surface of the Moon to search for water, Mission MoonCube's design involves sending groups of smaller, expendable, low-cost, single-purpose rovers called MoonCubes. Each MoonCube is specially designed to carry its own sampling and scientific equipment. For example, spectrometers on-board the MoonCubes specialize in detecting traces of water on the lunar surface using neutron spectroscopy, while ground penetrating radar systems detect water below the lunar surface. Since it is not certain where quantities of water may be present on the lunar surface, a wide range of probing and sampling equipment is highly beneficial and greatly increases our overall mission performance.

Using a series of small, expendable rovers greatly increases the overall coverage for Mission MoonCubed. During the operational phase of the mission, all of the MoonCubes will be communicating and sharing information with each other. This shared information includes location, terrain, and positive or negative identifications of water. This will allow each individual MoonCube to plan its future path intelligently in order to maximize the probability of locating and quantifying water.

In addition, the MoonCubes will collectively be able to cover a much greater portion of a lunar crater than a single multi-purpose rover. The MoonCubes are also expendable, which means that they are capable of traveling into inescapable locations to collect data near the end of their operation periods.

The current cost estimate for Mission MoonCubed is a rough order of magnitude estimate based on known facts and calculated expected cost values. It has been determined that the total cost of the mission is $475 million USD, which is within the $500 million USD (FY17) allocated for this mission as per the AIAA Student Design Competition requirements. This preliminary cost estimate compared to heritage from similar missions such as Spirit and Opportunity confirms that using a series of expendable rovers instead of a large, multi-purpose rover aids in lowering the cost of the entire mission. The MoonCubes for the mission are powered by single use batteries, which means that they have a relatively short mission life. These single use batteries are much cheaper than a long term power supply, such as a radioisotope thermoelectric generator. Additionally, less money needs needs to be invested to keep each of the MoonCubes safe in the lunar environment because they have relatively short mission lives. Nonetheless, the current rough order of magnitude cost estimate shows that Mission MoonCubed is on track to cost less than the $500 million USD (FY17) budgeted for this mission.

Lastly, using a series of small expendable rovers greatly increases the overall redundancy of the mission. For instance, a large number of different scientific instruments on many different MoonCubes will be used to search for water. If one of the instruments is yielding incorrect or inaccurate readings, a different instrument on a different MoonCube can be used to check the information determined by the first MoonCube. Additionally, using a number of individual MoonCubes makes navigation within a lunar crater much less of a risk. For example, if one of the MoonCubes were to become stuck near the beginning of the mission, there would be many other MoonCubes traveling throughout the crater still collecting data. The MoonCubes are also distributed between six different landing vehicles (called LunarBuses), which eliminates a single point of failure during the landing phase.

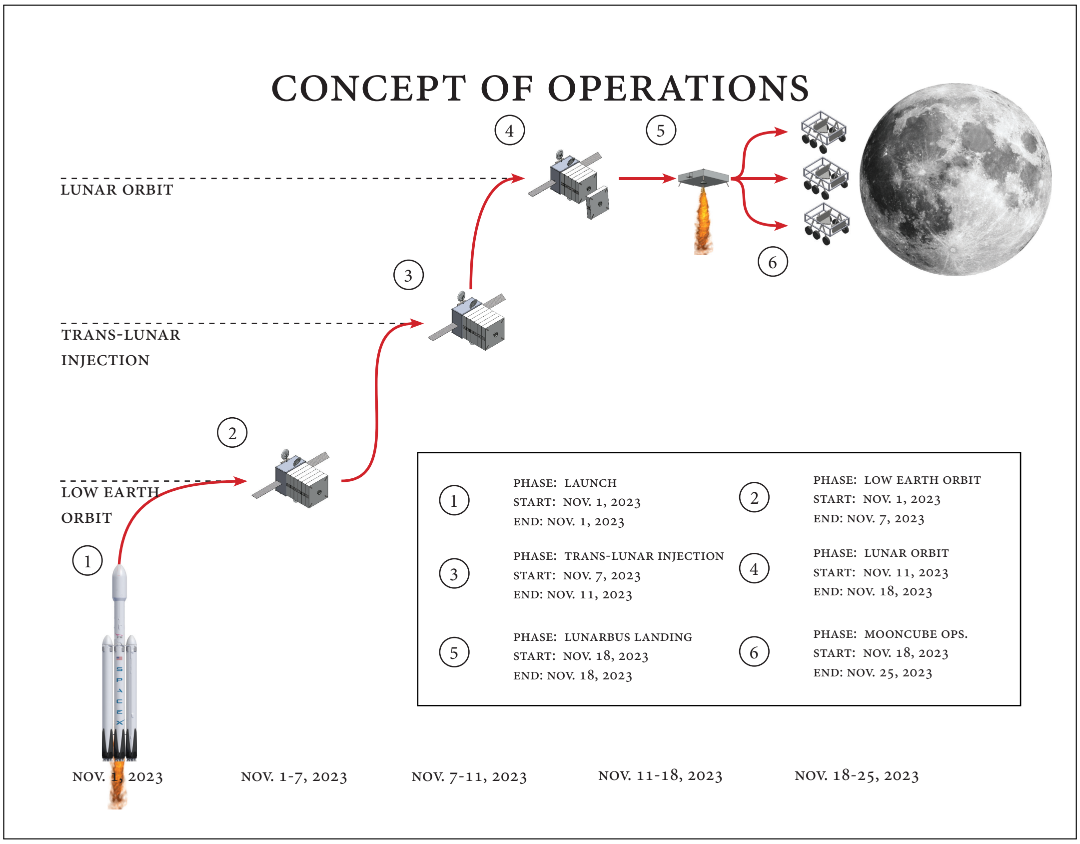


Figure 2: High-level mission overview

3.2 Mission Overview

Mission MoonCubed consists of the following three primary phases: (1) Transport (2) Deployment (3) Operation. Figure 2 serves as a high-level preliminary mission overview displaying the overall sequence of events for the mission. Within this figure, the transport phase includes launch, LEO, trans-lunar injection orbit, and lunar orbit. The deployment and operation phase all occur once the LunarBuses depart from the Mothership and deliver the MoonCubes to the surface of the Moon, shown as steps (5) and (6) in Figure 2.

3.2.1 Transport

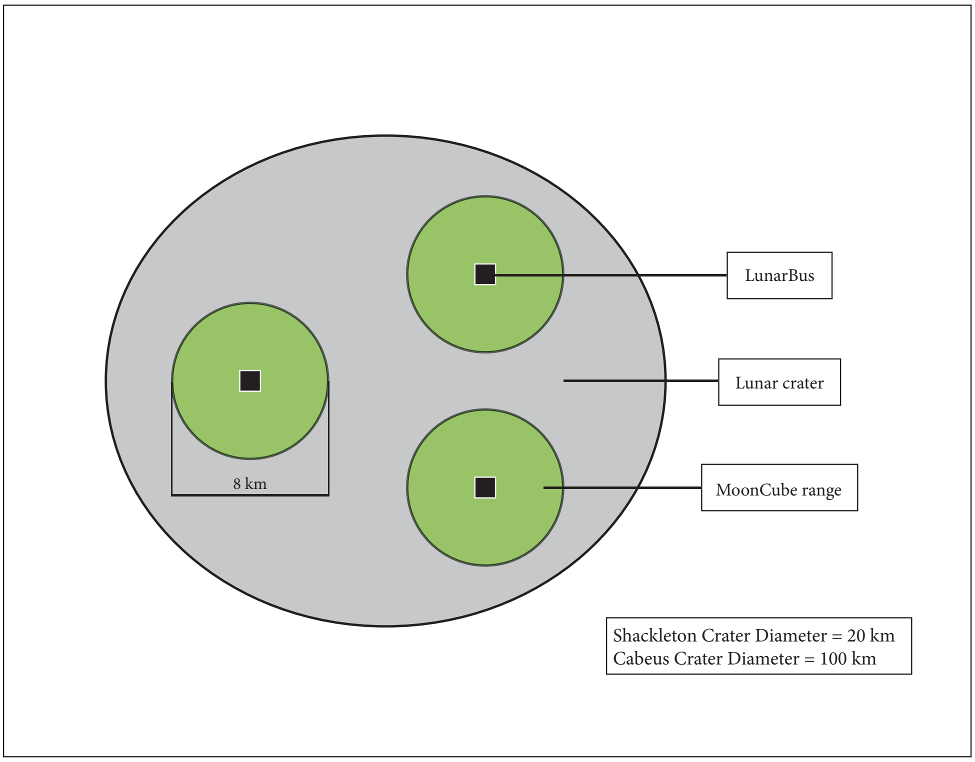
Phase (1) of the mission - the transport phase - begins with launch from Cape Canaveral on November 1, 2023 aboard a Falcon Heavy rocket. This launch vehicle will insert the payload into

LEO. The Mothership will then perform a ΔV of 3.1 km/s to transfer itself and the payload into a trans-lunar injection orbit. A ΔV of 0.82 will insert the Mothership into lunar orbit. The calculated time of flight from LEO to low lunar orbit is roughly 4 days. Once the spacecraft is in low lunar orbit, Phase (1) will come to an end.

3.2.2 Deployment

Phase (2) of the mission - the deployment phase - will begin when the LunarBuses depart from the Mothership. Six LunarBuses will be used in total in order to maximize the coverage area of the MoonCubes in two different craters. One LunarBus will be deployed with each orbital pass over a given crater until all of the LunarBuses have been deployed. Figure 3 shows an initial design of the LunarBus landing location and MoonCube coverage within a single lunar crater. The MoonCubes will operate within a 7.5 kilometer radius range around each LunarBus landing location.

Figure 3: LunarBus Landing and MoonCube Coverage



Using their on-board thrusters and attitude control systems, each LunarBus will descend to the lunar surface. The exact landing location within a crater will be determined by terrain data collected from the side-mounted GPR on each landing vehicle during descent. The landing locations of the LunarBuses will also be carefully determined to ensure the best communication between the LunarBuses and the Mothership, as well as ensuring solid communication lines between all MoonCubes. After the LunarBuses have landed at their selected locations within the craters, the MoonCubes will exit the LunarBuses and begin the operational phase. The landed LunarBuses now act as a data storage and communication hubs used to transmit MoonCube data to the Mothership, then from the Mothership to Earth.

3.2.3 Operation

Phase (3) - the operational phase of the mission - will commence after all of the MoonCubes have been deployed from their respective LunarBuses. Following deployment, the MoonCubes will take initial scientific readings just outside of the uncontaminated landing zone around each LunarBus. The respective LunarBus will then process this initial information and determine the most optimal route for each MoonCube to take in order to maximize the total sampling coverage for the MoonCubes collectively. As the MoonCubes travel along their calculated routes collecting data, they will continuously send information to their respective LunarBus. This constant relay of information and location between all MoonCubes will allow the LunarBuses to provide real-time updated travel information to each MoonCube in order to maximize mission performance and coverage. During the operational phase, the LunarBus will process and send important data collection information to the Mothership with each overhead pass of the crater. The Mothership will also process and store data before sending it back to Earth. The primary operational phase is expected to last for around 7 days.

3.3 Landing Locations

One of the most challenging parts of this mission is determining which craters on the Moon have the highest probabilities of containing significant and accessible quantities of water. It has been determined that the highest concentrations of water are likely to be in the polar regions and in deep impact craters because these regions are protected from solar heating which would otherwise vaporize the water. Several lunar probes, including Japan's Kaguya [1], India's Chandrayaan [2], and NASA's Lunar Reconnaissance Orbiter [3] have shown evidence of water on the lunar surface. Additionally, the Lunar Flashlight [4] and Lunar IceCube [5] are two planned NASA missions which both share the specific goal of of exploring, locating, and estimating the size of water ice deposits near the poles of the Moon from a lunar orbit. These missions are expected to be complete prior to when Mission MoonCubed will take place.

One of the most recent mission to the Moon - The Lunar Reconnaissance Orbiter (LRO) - provides the most up-to-date and detailed information describing crater locations most likely to contain significant quantities of water. During the mission, the LRO collected surface temperature and surface reflectively data from many different lunar craters. Lunar craters with a low enough surface temperature and a high enough surface reflectance were then noted as craters most likely to contain water ice on or near their surface. Pairing this information with locations that would be ideal for establishing a Moon base led to the decision of selecting to visit the craters of Shackleton and Cabeus for Mission MoonCubed. These two craters, along with their latitudes (positive north, negative south), longitudes (positive east, negative west), and diameter are listed in Table 2.

Table 2: Mission MoonCubed Landing Locations

Crater Name	**Latitude [°]**	**Longitude [°]**	**Diameter [km]**
Cabeus	-85.33	42.13	100.58
Shackleton	-89.67	129.78	20.92

Information retreived from [6, 7].

In addition to further research and trade studies, Mission MoonCubed is planning to use valuable information from both the Lunar Flashlight and Lunar IceCube to further refine which craters on the lunar surface have the highest probability of containing water. If successful, these missions will provide invaluable reconnaissance information when selecting possible landing sites. Additionally, Mission MoonCubed will increase the overall value of both the Lunar Flashlight and Lunar IceCube missions and will act as the preceding mission in the search for water on the Moon.

3.4 Mission Heritage

The Lunar Crater Observation and Sensing Satellite (LCROSS) was the spacecraft launched alongside the Lunar Reconnaissance Orbiter (LRO) with the goal of detecting water in the Cabeus crater near the lunar South Pole. The spacecraft went about this by impacting its upper stage into the crater and passing through the debris cloud to perform a spectral analysis. The spacecraft then transmitted that data back to ground control before ultimately impacting the lunar surface itself. Although the mission suffered an error resulting in the loss of more than half of the onboard propellant, it was ultimately a success, as NASA announced that water was detected on Nov 13, 2009. This mission successfully detected water on the Moon, which is primary objective of Mission MoonCubed. The LRO mission used a laser spectrometer to detect the presence of water from a debris cloud, which is the same technique that the Flat Moon Society plans to implement on the MoonCubes. Based on the information gathered from this mission, Mission MoonCubed plans to return to the Cabeus crater to locate and quantify sources of water [8].

The Mars Exploration Rovers (MER) are two identical Martian rovers developed with the goal of exploring the surface of Mars. Another Mars mission, Spirit and Opportunity, were deployed thousands of miles apart to perform identical missions. While contact with Spirit was lost in 2010, Opportunity has continued to operate as of April 2018. The MER program was created to study multiple points on the martian surface as efficiently as possible. To accomplish this, two identical rovers were constructed, which is the impetus of using multiple rovers in Mission MoonCubed to search for water in craters on the Moon [9].

The Apollo Missions' goals included not only achieving scientific supremacy for the United States by being the first country land a human on the Moon, but also to perform various scientific experiments and explore the Moon. Apollo 17 was the final mission of the Apollo Program. This mission contained a large scientific payload for geological surveying, sampling materials, and performing other tests such as lunar seismic profiling and a lunar surface gravimeter. The mission included a human crew and a Lunar Roving Vehicle for exploration purposes. Apollo 17 implemented the use of a human-controlled battery powered rover. This relates to our autonomous swarm of rovers in terms of structure and mobility requirements which will be used to explore the craters. Like Apollo 17, Mission MoonCubed also has primary and secondary objective goals of geologic surveying and sampling material, specifically to locate and quantify water resources [10].

4 Subsystems

The success of Mission MoonCubed will depend on the implementation and functional operations of ten subsystems, each of them carefully designed to match respective mission constraints and requirements. Implementation of a top-down system design method ensures a highly reliable overall system and will take into account all of the complex interactions between all subsystems.

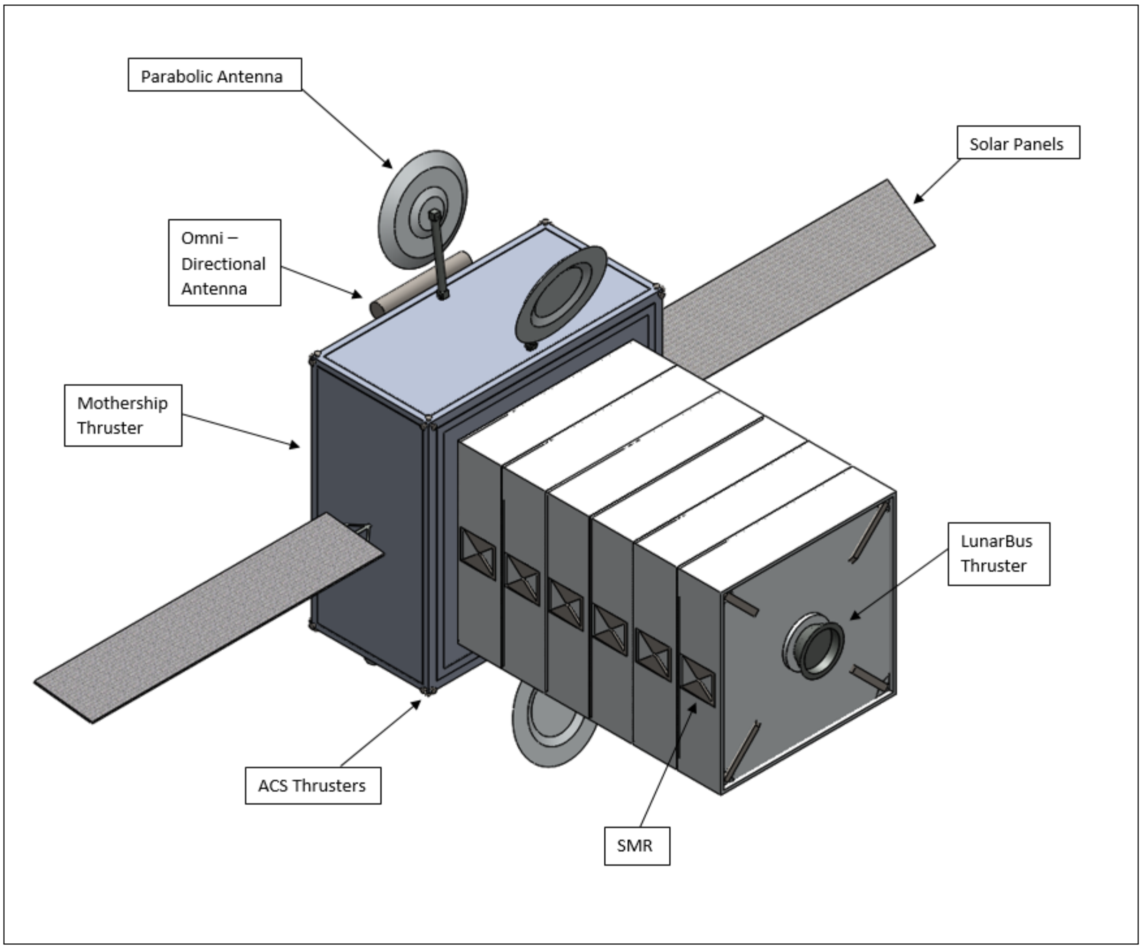
4.1 Structures and Mechanisms

The structures subsystem determines the geometry and specifies materials for all each mission vehicle and mechanism for Mission MoonCubed. Structurally, all vehicles must be able to withstand varying amounts of stress when carrying out the mission, including, but not limited to: launch, orbital maneuvers, and landing. The materials used in Mission MoonCubed were carefully selected by performing a material trade study, as shown in Table 3. The individual score for each material was calculated by multiplying the selected rating of the material by its respective material property (weight, density, etc.). The total score is simply the sum of all individual scores for each material property (Ex: Cost Score = Cost Weight x Cost), (Ex: Total Aluminum Score = Cost Score + Density Score + Strength Score + Temperature Score + Specific Strength Score). From this trade study, the primary materials implemented in structural designs are aluminum, Kevlar, and carbon composite.

4.1.1 Mothership S&M

The Mothership vehicle is shaped like a rectangular prism with solar panels on each side. The communication system's high-gain antennas are fitted on the sides of the Mothership. Bracing between each transport vehicle will feature a sandwich-like panel with a hexagonal core made of carbon composite (AS4) to stabilize each LunarBus. This material has a very high specific strength and can maintain form during the vibrations caused by launch and maneuvers. Each latch attached to the LunarBus will be made of titanium alloy beta-c for its high strength rating. The volume of

Figure 4: Mothership, LunarBuses, and Components



the Mothership is 33.59 cubic meters, while each LunarBus has a volume of 2.18 cubic meters. The total volume of both the Mothership and the LunarBuses are 46.64 cubic meters. The dimensions of the Mothership are 4 x 4 x 2 meters. The folding solar panels extend outward to a length of 5m and a width of 1.5m. These panels unfold using electro-pyrotechnic devices. The Mothership, LunarBuses, and relative components are shown in Figure 4.

For communication, the Mothership has four dish antenna arrays: two facing Earth and two facing the Lunar surface. The rocket engine mounted on the bottom of the vehicle is 1m long, and 1.5m in diameter at its widest point. There are 16 attitude control nozzles on the Mothership, each 0.05m long and 0.8m in diameter. The Mothership vehicle is shown in Figures 5, 6, 7, and 8.

Figure 5: Isometric View of Mothership

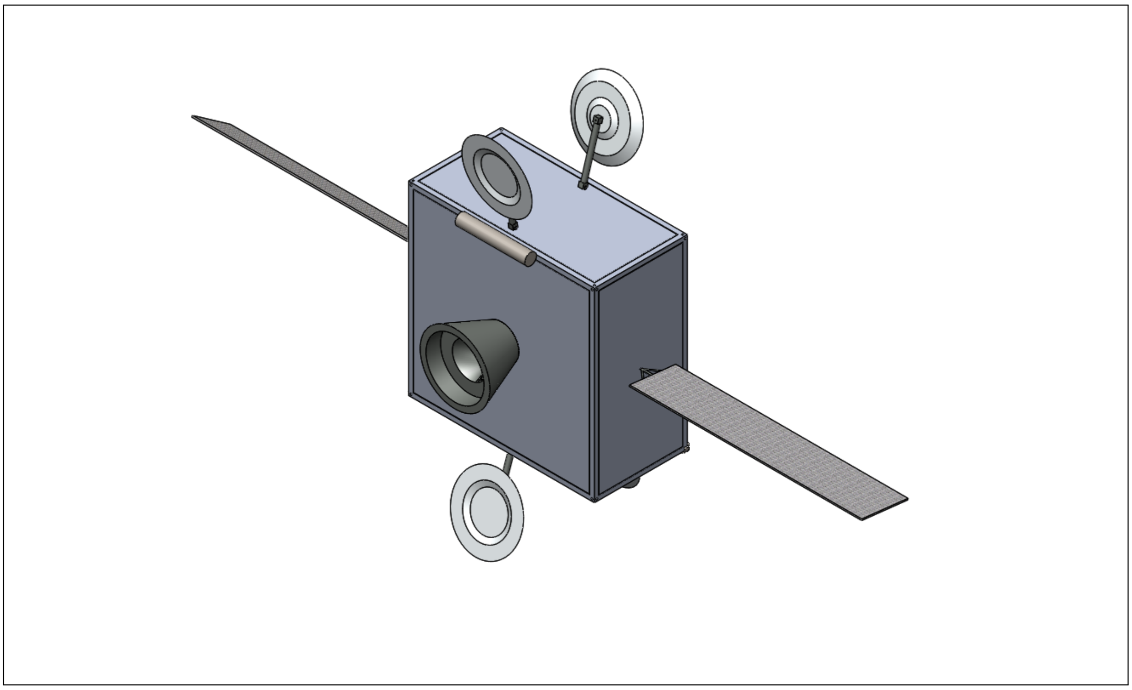


Figure 6: Front View of Mothership

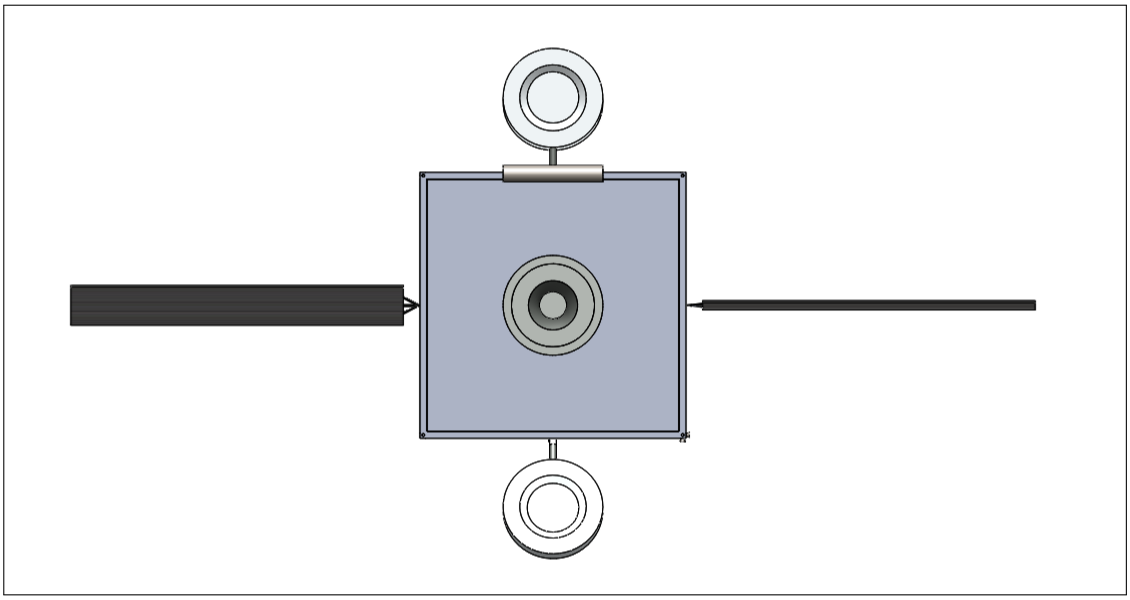


Figure 7: Top View of Mothership

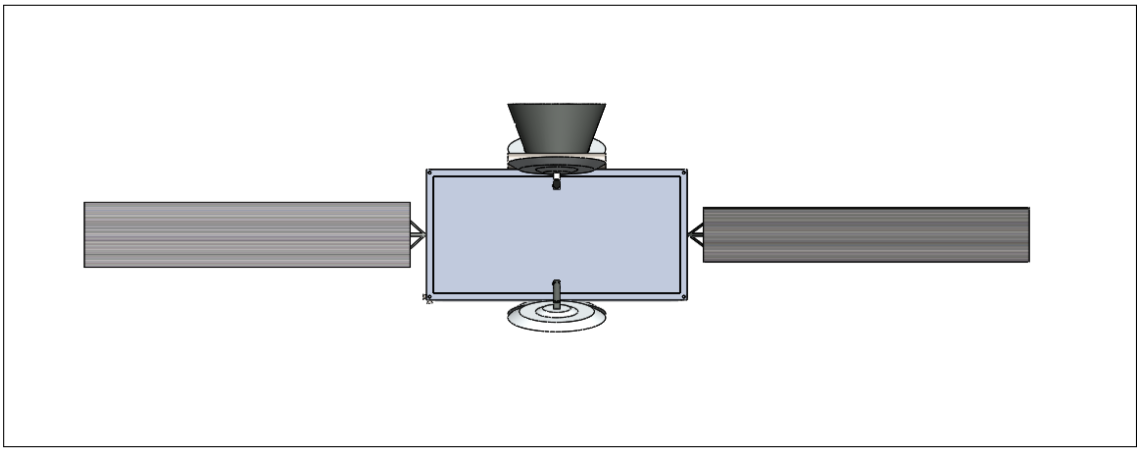
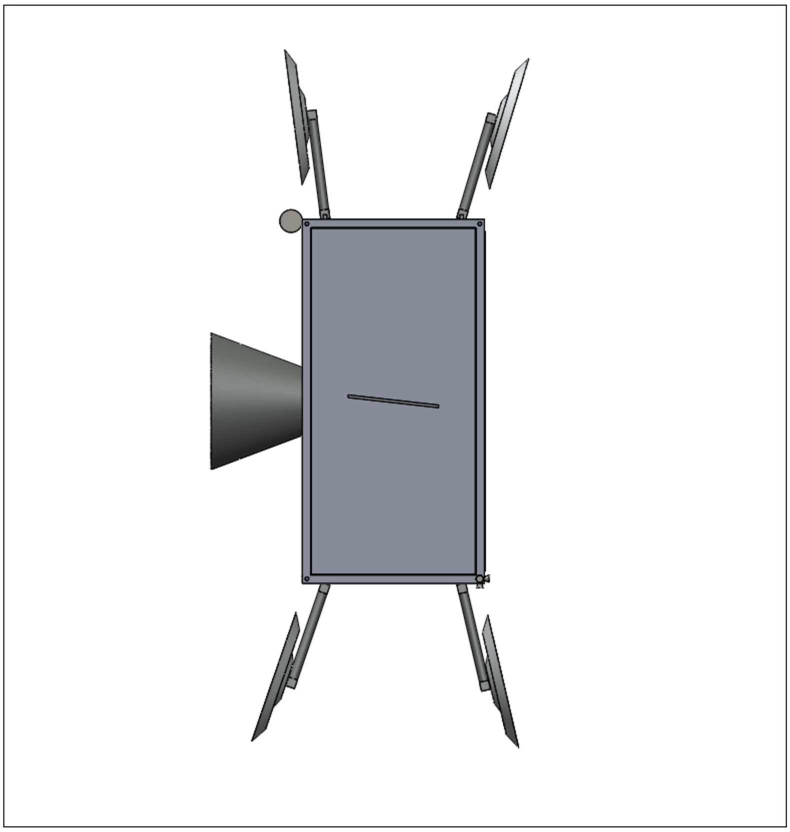


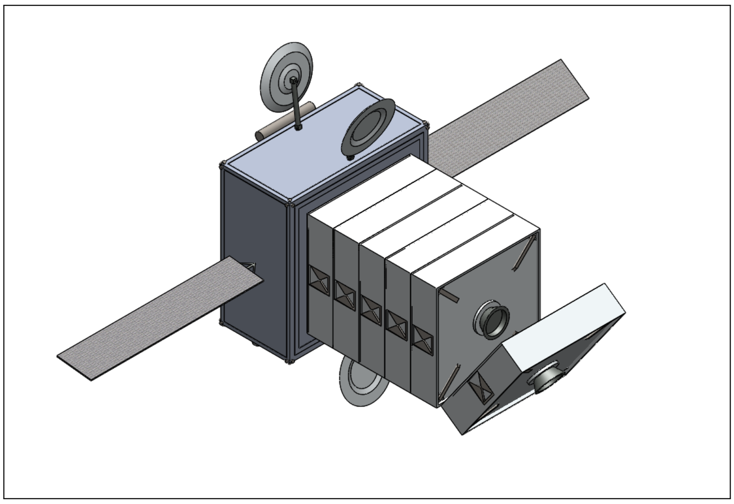
Figure 8: Side View of Mothership



4.1.2 LunarBus S&M

Six LunarBuses will be attached to the Mothership using latches and explosive bolts as a backup separation method. When the Mothership is in an appropriate deployment location in its orbit, the LunarBuses will detach from the Mothership as shown in Figure 9. Using the three separate transports to deploy MoonCubes across the each crater allows Mission MoonCubed to achieve exceptional coverage (data collection and sampling coverage of at least 600 square kilometers per crater).

Figure 9: LunarBus Deployment from Mothership



Each LunarBus needs to be structurally capable of carrying a payload of 2000 kg - the total MoonCube mass. The LunarBuses' primary purpose is to transport and release MoonCubes on the lunar surface. The structure needs to withstand the various stresses experienced during the lunar landing, but does not need to endure the lunar surface environment for an extended period due to the short mission duration of Mission MoonCubed. The panels and frames for both the LunarBuses and MoonCubes are made of aluminum. This decision was made based off of the trade study analyzing the various materials properties shown in Table 3.

Table 3: Material Trade Study

Material	**Cost per lb [USD]**	**Density [kg/m^3]**	**Strength [MPa]**	**Max. Temperature [K]**	**Specific Strength [kN m/kg]**	**Score**
Aluminum (2045 T4)	2.5	2712	450	523	204	0.8
Kevlar (KM2)	13	1350	3620	488	972	0.7
Carbon Composite (AS4)	10	4300	1450	488	2457	-0.2
Titanium Alloy (Beta C)	30	4420	1000	673	260	-15.4
Steel (AISI 1045)	0.9	7750	585	923	88	-1.0

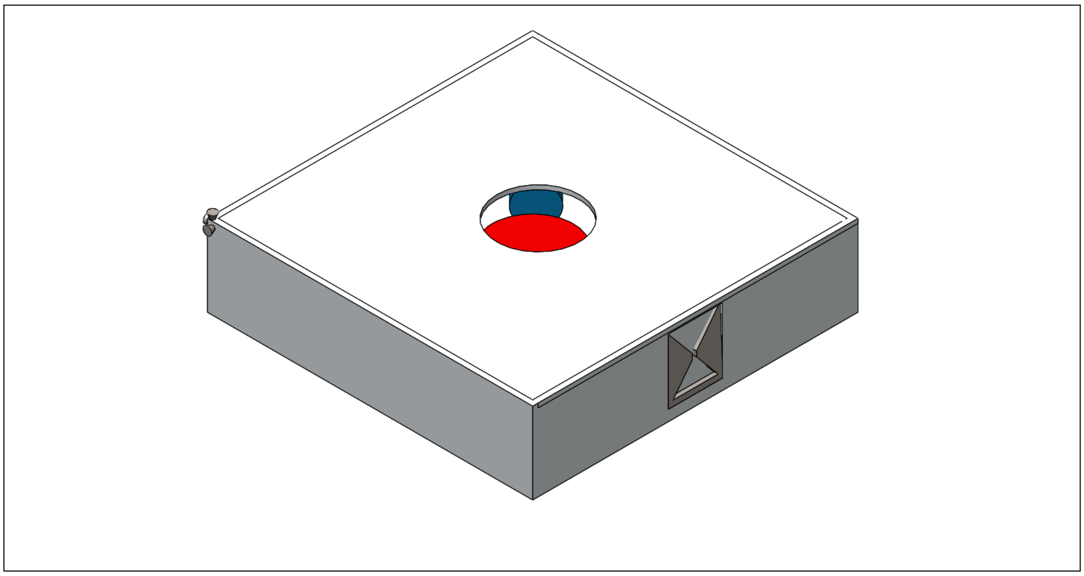
Information retrieved from [11, 12, 13].

Cost is weighted significantly higher in the trade study as a large amount of MoonCubes and LunarBuses need to be produced. The second highest weighted category was the density, as overall payload mass has a significant effect on the overall cost of the mission. Aluminum is rated very high in both of these categories, while also being able to withstand various vibrations. The specific strength and temperature ranges of aluminum fulfill all of the requirements of the mission.

The LunarBuses fit together when in storage configuration by the engine of one transport fitting into the next LunarBus. Each LunarBus is 3 x 3 x 0.75 meters. The engine nozzle is the same size as the Apollo landers (0.6m in length, with a max diameter of 1m). Similar to the main engine, the LunarBus thruster will fit into the next LunarBus when in storage configuration. Each LunarBus is equipped with 8 ACS thrusters on the top half of the vehicle. Each ACS thruster is each 0.05m long and 0.8m in diameter, as shown in Figure 10.

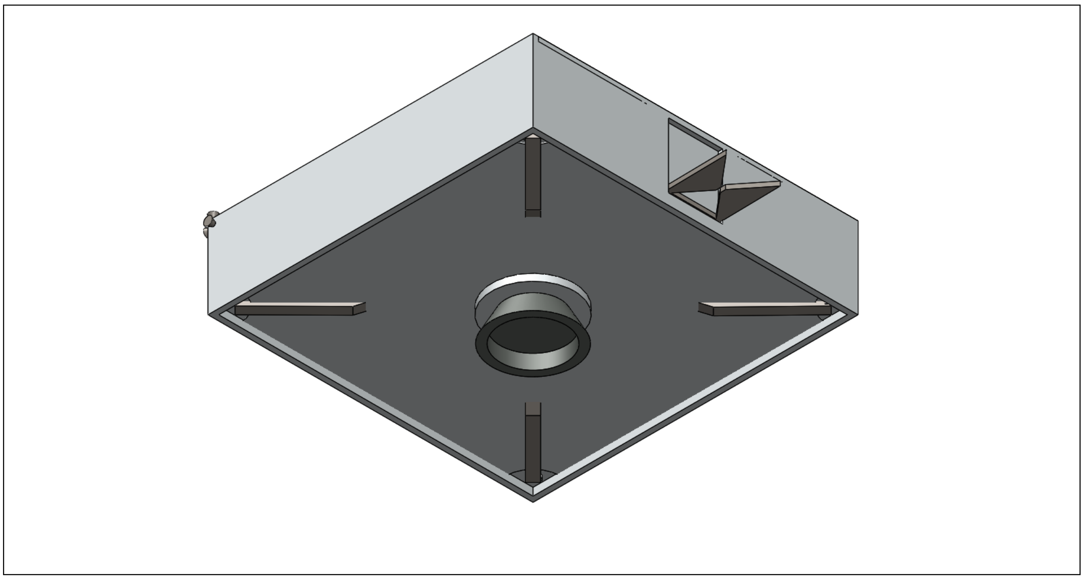
As a LunarBus approaches the surface, the side-mounted ground penetrating radar (SMR) of the LunarBus will deploy using a spring system. The SMR is larger than the RIMFAX GPR used

Figure 10: Isometric View of a LunarBus



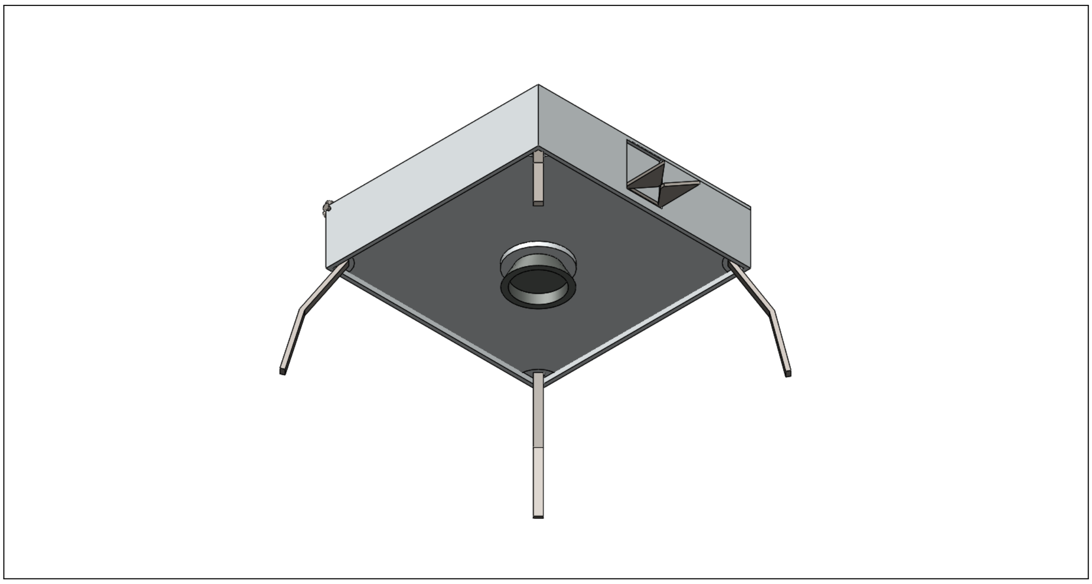
for MoonCubes, extending 0.6m away from the vehicle. This structure needs to be able to perform various adjustments as the LunarBus alters its course during descent, along with vibrations from the thrusters and the main engine. A LunarBus in decent is shown in Figure 11.

Figure 11: LunarBus in Descent



When a LunarBus nears the surface, four legs made of carbon composite AS4 extend outward and brace for impact using springs and dampers. Carbon composite AS4 is used for this crucial part of the mission for it high specific strength. These legs are 1.25m long to assure that the nozzle does not strike the ground during landing, as shown in Figure 12. Although not effectively shown in the diagrams, the legs include a suspension system that enables the vehicle to land balanced on uneven terrain.

Figure 12: LunarBus Landing Legs

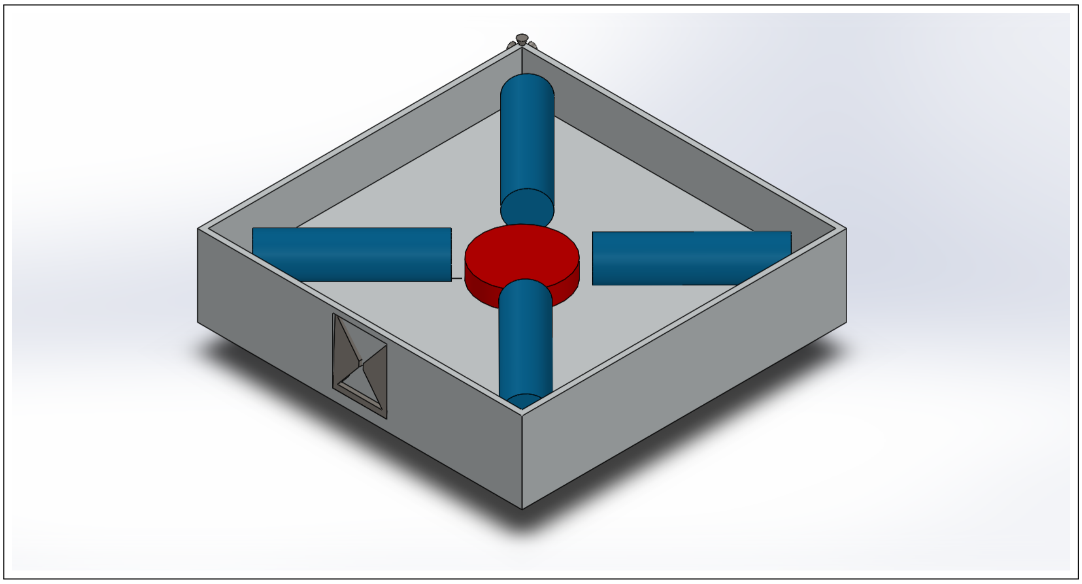


Once a LunarBus has landed, the bottom plate will detach from the main frame and drop onto the surface. This plate is initially held in place using latches and explosive bolts, much like how the LunarBuses separate from the Mothership. All 50 MoonCubes will be stored on this plate and will have the ability to exit in any direction once the plate has been deployed. This deployment method was selected so that there was not a single point of failure during MoonCube deployment. An example of the MoonCube deployment from a LunarBus is shown in Figure 13.

The upper half of the LunarBus is where the fuel tanks are located. The four fuel tanks are for the main thruster and the ACS thrusters, while the smaller tank in the middle stores helium for pressurization of the fuel tanks. These components are shown in Figure 14.

Figure 13: MoonCube Deployment from LunarBus

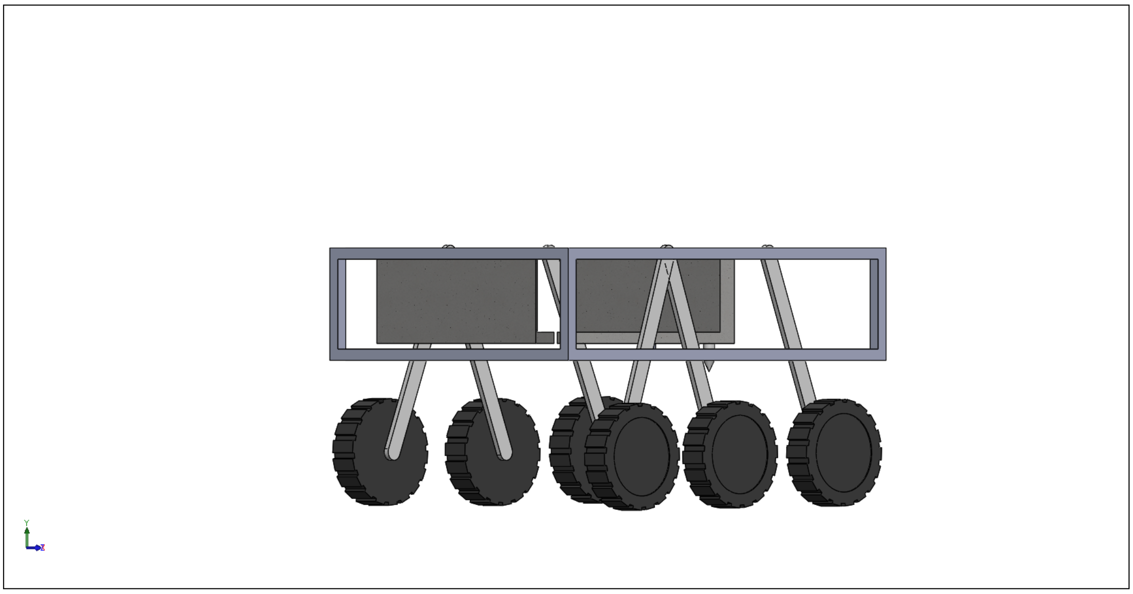
Figure 14: Fuel Tanks Within a LunarBus



4.1.3 MoonCube S&M

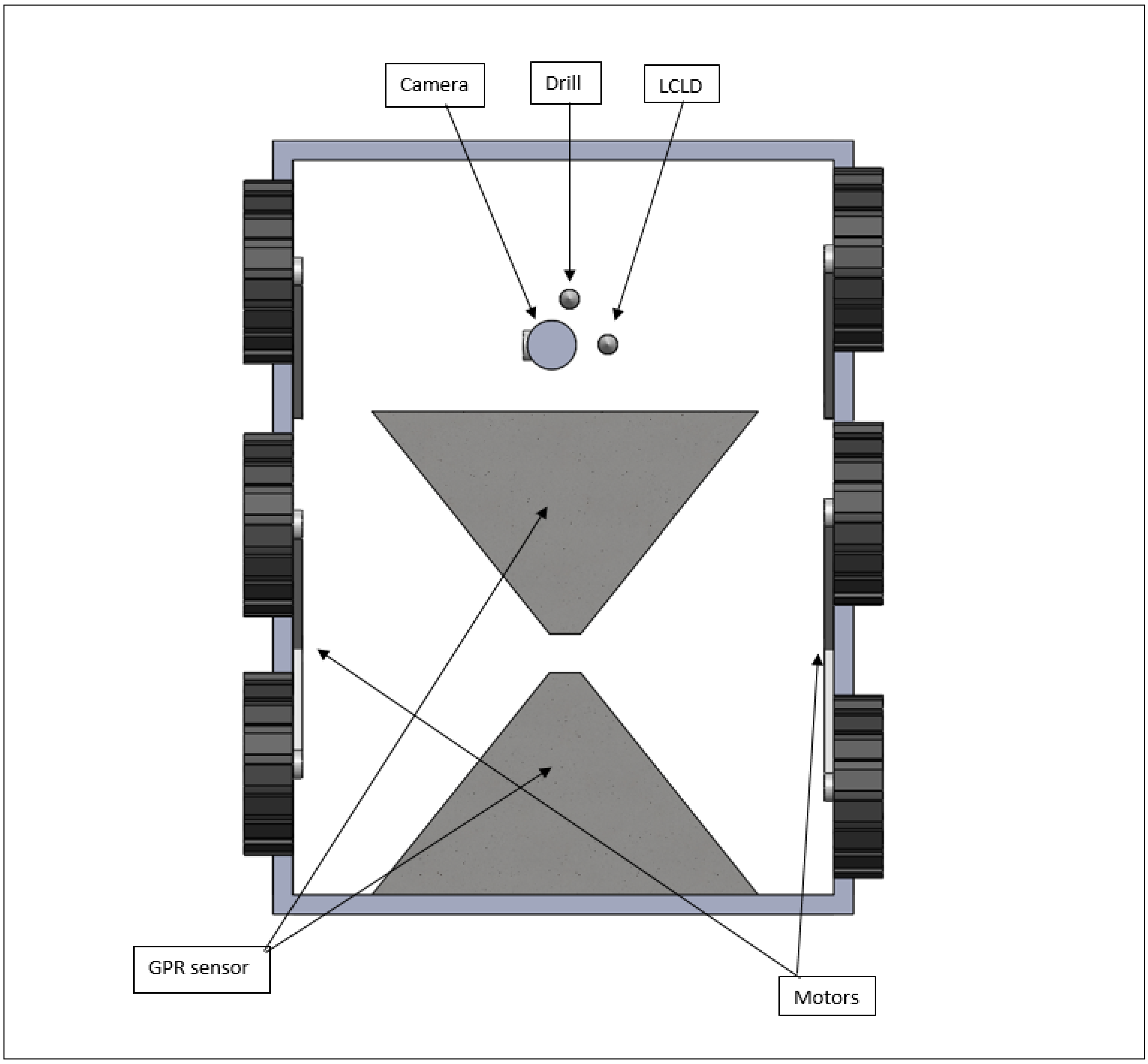
The body of the MoonCubes are made of lightweight aluminum 7068 which allow them to move easily across the lunar surface. This material was selected due to its high tensile strength despite it's low mass. Other materials were considered but all were too expensive because of the large amount of MoonCubes being produced. The dimensions of a MoonCube are 0.4 x 0.3 x 0.1 meters. MoonCube wheels are derived from those used on the Curiosity rover which use a similar suspension system composed of differentials, rockers, and bogies. This wheel system can effectively move across the unpredictable lunar surface. The wheels themselves are made of aluminum with titanium spokes for stability. Each wheels dimensions are 9cm in diameter and 3cm in width. The wheels will also be equipped with a rubber tread to improve traction on lunar regolith, as shown in Figure 15.

Figure 15: MoonCube Body and Wheels



The components within the MoonCubes consist of various sensors and scientific instruments, all attached using aluminum arms. Each sensor and instrument is shown in Figure 16.

Figure 16: MoonCube Sensors and Instruments



4.2 Launch Vehicle

The launch vehicle is a key component in the transport phase of Mission MoonCubed. The launch vehicle will be responsible for transporting the Mothership and LunarBuses prepackaged with the MoonCubes. Determining a launch vehicle is crucial, as it allows the rest of the mission to be planned out according to budget, volumetric-space, and payload weight requirements. The selected launch vehicle needs to be able to transport a total payload of 30,390 kg to LEO. In addition, the launch vehicle will need to have a fairing large enough to fit the maximum dimensions of the payload of 8.5 meters in height and 4 meters wide.

In order to meet the payload and mission requirements, the Falcon Heavy rocket from SpaceX was selected as the best choice for the launch vehicle. Falcon Heavy will launch the Mission MoonCubed payload from Cape Canaveral Air Force Station in Florida. The Falcon Heavy launch vehicle has a payload capacity of 64 metric tons to LEO, which is more than sufficient for Mission MoonCubed's total payload of 30,390 kg. The fairing on the Falcon Heavy has an internal height of 13.1 meters and is 5.2 meters wide, which is large enough to accommodate the maximum dimensions of Mission MoonCubed's payload of 8.5 meters in height and 4 meters wide. Also, Falcon Heavy is the most cost effective compared to other launch vehicles, costing only $90 million per launch. Similar launch vehicles, such as the Delta IV Heavy, the Long March 5, and the Vulcan cost $350 million, $650 million, and $350 million, respectively. Ultimately, launch costs using the Falcon Heavy vehicle would only account for 18% of the entire mission budget, leaving the rest for vital mission research, sub-system development, fabrication, and equipment. Further, SpaceX has shown good heritage with its Falcon 9 rocket by successfully completing 51 of 53 launches, and the expanded Falcon Heavy architecture has completed a successful test launch. It is expected that the similarities between the Falcon 9 and Falcon Heavy designs will lead to a similar level of reliability for the Falcon Heavy.

4.3 Propulsion

The propulsion subsystem determines the primary engines, attitude control thrusters, propellant types, and propellant masses for the Mothership orbiter and LunarBus landers. The functional requirements for propulsion for the LunarBus include descent from lunar orbit to the lunar surface and attitude control. Functional requirements for the Mothership orbiter include an orbital transfer from LEO to lunar orbit, orbital maintenance, and attitude control for stationkeeping. The propulsion system will also involve a redundant series of thermocouples, pressure transducers, and valves to monitor the fuel status and thrust output.

4.3.1 Mothership Propulsion

The Mothership will use a gimballed Aerojet AJ10-190 with a gimbal angle of $\pm 6°$ as a primary engine for transfer into lunar orbit from LEO and 16 Moog 5 pound-force model ACS engines for attitude control and orbital maintenance. Both systems will use hypergolic propellant consisting of monomethylhydrazine (MMH) and mixed oxides of nitrogen (MON). Having a primary engine and ACS using the same propellant type reduces complexity and mass with regards to tanks and piping. The AJ10-190 has successful mission heritage for an orbital transfer maneuver from LEO to lunar orbit for the Space Shuttle Orbital Maneuvering System and can produce an ISP of 313 seconds [14]. A ΔV of 3.13 km/s will be required for TLI and 0.82 km/s for insertion into lunar orbit.

Hypergolic propellants ignite on contact, making them ideal for short bursts of thrust needed for satellite maneuvering. The ACS will be responsible for stationkeeping to properly direct the antenna for communication of the Mothership orbiter as it passes overhead the LunarBus landers on the surface. The propulsion system will include two evenly distributed MMH and two MON tanks for redundancy and a helium tank containing 125 kg of helium to pressurize the propellant. The total propellant mass of the Mothership is 10,760 kg with a fuel to oxidizer ratio of approximately 3:5.

4.3.2 LunarBus Propulsion

The LunarBus propulsion system will function similarly to the Lunar Descent Stage of the Apollo missions. It will implement one main AJ10-190 engine with a gimbal angle of $\pm 6°$ on the bottom of the vehicle to control descent velocity as well as 8 Moog 5 pound-force ACS thrusters on the top half of the vehicle. The ACS thruster will be used to stabilize the landing and de-spin the lander if necessary. Like the Mothership, the landers will use MMH and MON hypergolic propellant with two evenly distributed tanks for each fuel and oxidizer, 1020 kg of total propellant with a fuel to oxidizer ratio of 3:5, and a helium pressurant tank containing 22.5 kg of helium

4.4 Ground Control

The Ground Control Subsystem (GCS) will allow the ground control team to monitor mission status based on sensor telemetry and data received via the Mothership and correct any discrepancies to the mission.

GCS will communicate with the Mothership through the Near Earth Network (NEN). Because of this, the GCS team will have to work directly with members from the Goddard Space Flight Center Ground Network project (responsible for maintaining the NEN) to ensure system interoperability. The Ground Control Station will be set up in Pasadena at JPL's Space Flight Operations Facility due to its heritage of autonomous exploration missions. The Johnson Space Center was considered due to its history with Moon missions (Apollo) [16]. However, it was not selected as it specializes in manned missions.

Throughout Mission MoonCubed, several teams will have major responsibilities to ensure all areas of ground control are working effectively. The Software Analysis team monitors the accuracy of the data being received from the Mothership, as well as the data communicated between the Mothership and LunarBuses, and between LunarBuses and MoonCubes. Operation Engineers monitor the overall health of the spacecraft. This includes ensuring that any damage taken does not affect spacecraft operability. These teams are responsible for monitoring and first-line error fixing. The Navigation Team monitors the trajectories of the Mothership and LunarBuses. It will also ensure that MoonCubes are navigating correctly. If an issue occurs, the team can adjust the flight path accordingly, although adjustments will be done primarily autonomously. The Command Team is responsible for overseeing the mission, as well as ensuring the data is processed for the end user.

In terms of requirements, ground control will be mission critical. The ground station must be able to transmit data and commands remotely if needed. The ground control teams will provide support in debugging when something goes wrong. The Ground Control Subsystem will be responsible in creating a secure network to prevent catastrophic mission failure. Ground control will work with the command and data handling system to store all the mission data and develop communication from the Mothership to the MoonCubes. Power and Propulsion subsystems will work, also, with ground control in terms of sensor data interpretation.

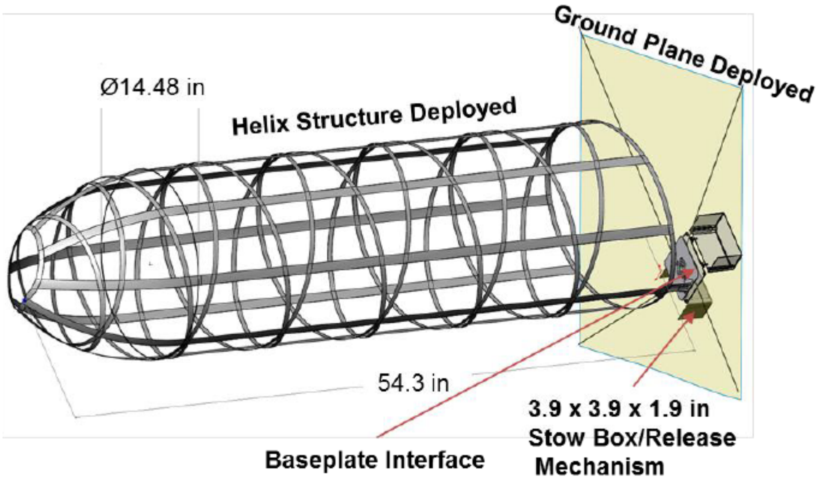
4.5 Communications

The communication subsystem of Mission MoonCubed is divided into three distinct areas: (1) surface to surface, (2) surface to lunar orbit, and (3) lunar orbit to Earth. As one of the key aspects of the mission architecture is to reduce costs, only UHF and S-band communication systems will be used, and COTS hardware will be incorporated whenever possible. UHF band systems were previously used on earlier planetary exploration missions such as the Mars Exploration Rovers and Curiosity to communicate with orbital hardware. Since the Moon has no atmosphere, there will be no atmospheric interference. This allows the focus to be on data rates and power usage rather than signal power and attenuation. Multiple missions to the Moon, such as the Apollo missions, have used the S-band in the past. It is also important to note that the Near Earth Network (NEN) allows for nearly uninterrupted S-band data links in lunar orbit, which negates the band's low data rate when compared to the X and Ku bands. As the S-band uses less power for a given signal strength, this is very desirable.

The surface to surface component of the communication subsystem will allow data to be transferred to and from the MoonCubes and from MoonCubes to LunarBuses. This system will be based solely on the UHF band, as it requires less power than other systems and has been used on previous rover missions. Each MoonCube is equipped with a single low-gain UHF monopole antenna that will allow it to communicate with its respective LunarBus. A LunarBus has four low-gain monopole antennas to allow for the large amount of data transmission required to send and receive data from its respective group of MoonCubes and other LunarBuses. This was done as a high-gain antenna must be pointed at its target, while low-gain antennas are omni-directional. The low-gain antennas used on both MoonCubes and LunarBuses will be derived from from the Mars Exploration Rover (MER) UHF system. The MER UHF antenna uses 5 Watts when receiving and 45 Watts when transceiving, weighs 1kg, and has a data rate of 256 kbit/s [17]. The LunarBus to MoonCube communications link will require 197 Watts of power to utilize all four MER derived antennas with a combined data rate of 1800 kbits/s being transferred to all of a LunarBuses' assigned MoonCubes.

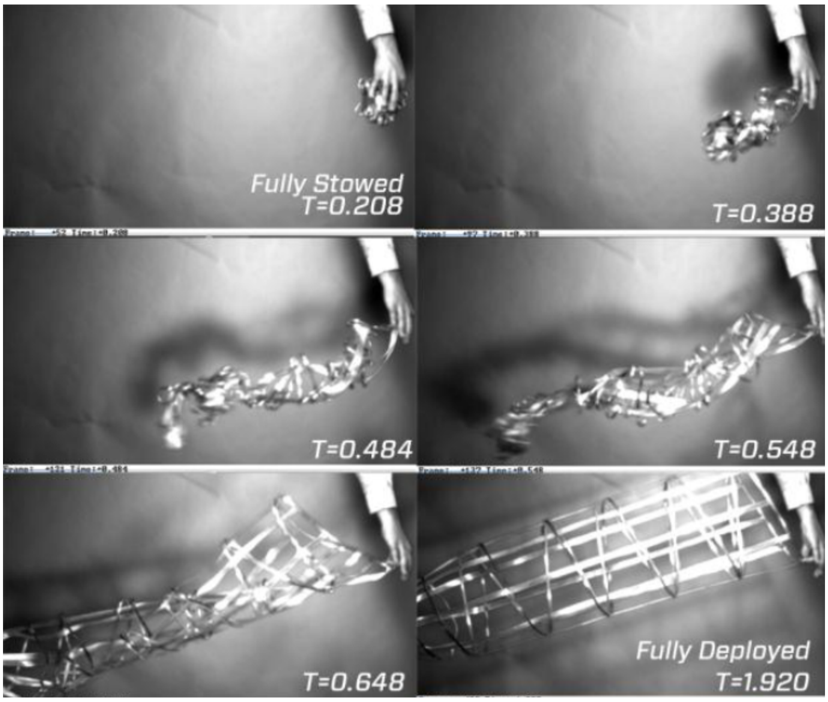
The UHF band will also be used for surface to lunar orbit communications. LunarBuses will be equipped with a Deployable Helical high-gain Antenna for Nano-Satellites (DHANS) UHF antenna to facilitate high data rate communications with the Mothership [27]. A deployable antenna, as shown in Figure 17 and Figure 18, will be used to prevent damage and reduce storage volume in the lunar injection phase of Mission MoonCubed. The power required for each LunarBus to transmit 578 kbit/s to the orbiting Mothership is 132 Watts when only the DHANS antenna is used. If DHANS becomes inoperable, the LunarBus will temporarily halt surface to surface transmissions and use its low-gain UHF antennas to communicate with the Mothership. This will result in a serious reduction of data rate to 230 kbit/s and a power consumption of 180 Watts. To ensure that enough power is available for surface to orbit communications, all surface activities will be halted until the Mothership has passed overhead. The Mothership will be equipped with two two meter high-gain UHF band antennas to send and receive data from the LunarBuses. As only two craters will be explored, each antenna will be employed per communication cycle.

Figure 17: Fully Deployed DHANS [27]



For lunar orbit to Earth communications, a S-band link between the Mothership and the NEN will be implemented. The NEN was selected as it provides higher data and availability rates than the Deep Space Network [18]. The Mothership will be equipped with two two meter high-gain S-band antennas to communicate with NEN. An omni-directional S-band antenna will also be included to provide command and control during maneuvers and in case tumbling occurs. The Mothership will require 25.5 Watts of power to transmit 3.5 Mbits/s to NEN. In turn, NEN will require 29 mW

Figure 18: DHANS Deployment Phases [27]



of power to transmit the 256 Kbits/s needed for daily command and control of the mission. In emergency situations, NEN will be able to upload 256 Mbits/s to the Mothership when needed.

4.6 Command and Data Handling

There will be three separate C&DH systems that will make up the entire C&DH architecture for Mission MoonCubed. The C&DH subsystem on board the Mothership will be responsible for executing station keeping maneuvers in order to establish and maintain a lunar orbit. The system will also be responsible for executing the deployment of the LunarBuses. The C&DH system onboard the individual LunarBuses will be responsible for orchestrating the maneuvers necessary to guide the lander to a predefined location on the lunar surface. During descent, the lander's C&DH system will be processing the ingress of data coming from the onboard IMU and GPR in order to gain information about the composition of surface below it, which will ultimately affect the final landing location. After touchdown, the LunarBus C&DH system will send initialization commands to the MoonCubes which will disembark from the LunarBuses. The C&DH system onboard each of the individual MoonCubes will be responsible for executing commands that will guide the drone through a predefined course around the crater surface. It will also monitor the thermal and power systems to ensure that all electronics will be within operational conditions. Data will be received from the drones prospecting sensors which will be transmitted for relay back to ground control.

4.6.1 Mothership C&DH

The Mothership's C&DH system will be responsible for interfacing with the Communication and GNC systems. Its responsibilities will involve receiving commands from communications, and translating them into commands for the GNC system in order to execute operations. The system will also be receiving periodic data dumps from the LunarBuses. These data dumps will be cached via the onboard SSRs. During the Mothership's next optimal communication window with Earth, the data will be transmitted to Ground Control via the NEN.

Hardware & Software

Computer: BAE RAD5545TMSBC x2

The BAE RAD5545TMSBC was chosen as the primary Mothership computer for two reasons:

1. Heritage
2. Radiation resistance

The BAE RAD5545TMSBC is a newer version of the BAE RAD750 architecture [29]. This architecture has been used in several important missions such as Curiosity Rover [30], Kepler Space Telescope [31], and the Lunar Reconnaissance Orbiter. This particular architecture enjoys all of the benefits of the previous version, in addition to several performance improvements. This computer is also radiation hardened. Due to the importance of the Mothership's C&DH system to the rest of the mission, a failure for any reason would be catastrophic. Radiation hardening helps to ensure successful operation of the Mothership during the lifetime of the mission.

Software: Wind River's VxWORKS

Wind River's VxWorks OS was chosen as the operating system for the Mothership for three reasons:

1. Heritage
2. Reliability

3. Support

VxWorks has been used on several notable missions such as DAWN, Curiosity, and Juno [32]. VxWorks is also extremely reliable within the realm of RTOS' already available. Due to the importance of successful operation of the Mothership, reliability is the most important consideration. VxWorks is also backed by the company Wind River who offers timely support for their software.

The only negative aspect of using VxWorks is the licensing costs for the software itself. Currently, the price is listed at $250,000 USD for a mission length of one year [33]. This is the reason that VxWorks was not a candidate for the mission's other C&DH systems.

SSR: SwRI's Solid State Recorder

SwRI's Solid State Recorder was chosen as the main Solid State Recorder of this mission for three reasons:

1. Storage
2. Bandwidth
3. Interfaces

Because of the nature of the mission's data handling architecture, the Mothership will play an important role in relaying rover data back to Ground Control. Due to this, it will require significant storage capacity for data. This SSR has a listed capacity of 1.5 Tb on a single 6U mass-memory module [34]. There will also be periods of the mission — determined by orbital positions — when the Mothership will experience a high ingress and egress of data. Being able to read and write data from the disk at high rates will be paramount during those times. This SSR also has several interfaces available, which allows for flexibility in the hardware. The current listed I/O rates are listed at aggregate input of 25 Gbps and digital data output rates of 20 Gbps [35].

Interface with Propulsion

The Mothership's C&DH system will issue all necessary controls to the onboard propulsion system. The monitoring of the Engine Control will be delegated to the engine's onboard engine controller.

Interface with Communication

The Mothership's C&DH system will receive data from the Communications subsystem from the MoonCubes and LunarBuses on the ground. That data will be stored on the Mothership via the SSR. During transmission periods, the Mothership will then be able to read this data from the SSR and relay it back the to communication system, and ultimately to Ground Control via the NEN.

Interface with GNC

The Mothership's C&DH subsystem will interface with the various GNC modules onboard in order to receive information about the dynamics of the ship, as well as sending commands to the system in order to make station-keeping maneuvers.

Interface with TCS

The Mothership's C&DH subsystem will interface with the Thermal Control System in order to monitor internal temperatures to maintain operating conditions for the onboard electronics.

System Block Diagram

A system block diagram for the Mothership Command and Data Handling subsystem is shown in Appendix 7.6. This diagram shows how the computing system of the Mothership interacts with each of the other subsystems, and what types of commands and data are sent between the different subsystems.

4.6.2 LunarBus C&DH

The C&DH system for the LunarBus will be responsible for controlling the GNC and Propulsion system during the lander's decent to the lunar surface. After the drones have been deployed, the lander will maintain communications with the drones, acting as the central node in the drones' mesh network. The lander's C&DH system will also be responsible for distributing commands to the drones from the orbiter, as needed. Data received from the lander's communication system will be cached on the lander's onboard SSRs. This data will then be relayed to the orbiter during the ideal transmission window.

Hardware & Software

Computer: Endursat Cubesat Onboard Computer x2

The Endursat Cubesat Onboard Computer was chosen for three reasons:

1. Cost
2. Availability
3. Interfaces

The most important reason that this computer was chosen was cost. The Endursat has a list price of $3,500 USD [36]. This is significantly less than competing traditional computers, and this is mainly due to the prevalence of CubeSat hardware and the lack of radiation hardening. The loss of radiation hardening should not negatively impact the overall mission due to the very limited TOF of the LunarBuses. Once deployed they will be shielded from radiation by the geography of the lunar surface, and the radiation on the surface should be negligible given the lifetime of the mission. Also, due to the large number of LunarBuses, the cost of traditional space ready computers for each the landers would have been prohibitively expensive. With respect to the number needed, the Endursat computers are highly available due to their prevalence in the CubeSat industry. This will make sourcing and potentially replacing them much easier.

This mission will have fairly intensive interfacing requirements due to the breadth of the hardware being used on the LunarBuses. As a result, the main computer will need to be able to communicate over many of these interfaces. Another important concern is the amount of custom software required to interface with the hardware. Using prevalent off the shelf hardware like the Endursat will enable minimal modifications to be made in software to accommodate it.

SSR: Compact SSDR

The Compact SSDR was chosen as the LunarBuses' data recording solution because of its integration with the cube computer [37]. It also is highly expandable in a U form factor. This will accomplish the requirements for data storage, and redundancy.

Software: KubOS

The choice to use use the KubOS software was mainly due to the easy ability to integrate with hardware. It is also an open-source RTOS opposed to VxWorks. This OS will act to reduce the overall cost of the C&DH system due to a decrease in man hours to implement, and software licensing fees. This OS also has a large amount of boilerplate libraries available which will reduce the total total person-hours required to develop software.

Interface with Propulsion

The C&DH system onboard the LunarBuses will communicate with the onboard propulsion Engine Management Controller. This will allow control of the craft during decent onto the lunar surface.

Interface with Communications

The C&DH system onboard the LunarBuses will communicate with the onboard communications system in order send and receive data and commands.

Interface with GNC

The C&DH system onboard the LunarBuses will communicate with the onboard GNC modules in order to receive data about the crafts attitude, as well as to issue attitude adjustment commands.

System Block Diagram

A system block diagram for the LunarBus Command and Data Handling subsystem is shown in Appendix 7.6. This diagram shows how the computing system of the LunarBus interacts with each of the other subsystems, and what types of commands and data are sent between the different subsystems.

4.6.3 MoonCube C&DH

The MoonCubes will each have individual C&DH systems which will be responsible for how the vehicles maneuver across the lunar surface, when to take data samples/measurements, and interfacing with the communication system for sending data and receiving commands. Commands from the LunarBuses will serve purposes such as updating the preloaded travel route, or updating the cadence of data sampling. The drone C&DH system will also be responsible for maintaining internal environmental conditions in order to maintain proper operational conditions for the onboard electronics. Due to the limited battery life of the drone, the C&DH system will also be responsible for idealizing the operating behavior of the drone in order to minimize power consumption, thus extending the life of the mission.

Hardware & Software

Computer: Endursat Cubesat Onboard Computer

The Endursat Cubesat Onboard Computer was chosen as the primary C&DH computer onboard individual MoonCubes for the same reasons as mentioned in LunarBus section.

Software: KubOS

KubOS was chosen as the onboard OS for the MoonCubes for the same reasons as mentioned in the LunarBus section.

SSR: SD Card

The Endursat has a built in slot for traditional SD cards to provide data permanence. This will allow for several Gigabytes of data storage.

Interface with Propulsion

The C&DH system onboard the MoonCubes will communicate with motor controllers onboard in order to move the cube across the lunar surface.

Interface with Communication

The C&DH system onboard will communicate with the communications system in order to receive commands from the LunarBuses as well as send data back.

Interface with GNC

The C&DH system onboard will communicate with the GNC system in order to receive data from the various sensors and science modules, as well as various hardware controls.

System Block Diagram

A system block diagram for the MoonCube Command and Data Handling subsystem is shown in Appendix 7.6. This diagram shows how the computing system of the MoonCube interacts with each of the other subsystems, and what types of commands and data are sent between the different subsystems.

4.7 Guidance, Navigation, and Control

The system level requirements for Guidance, Navigation, and Control for the Mothership orbiter include navigation for the orbital transfer maneuver from LEO to lunar orbit and determination of attitude and orbital position. Once in lunar orbit, the Motherhship will release the latches holding the LunarBus landers in place or implement the explosive bolt failsafe if necessary. Requirements for the LunarBuses are determination and control of descent velocity and attitude to achieve a level landing with an impact velocity under 1 m/s. Once on the surface, each LunarBus will deploy its ramp to release the swarm of MoonCubes. Requirements for the MoonCubes include navigation of the rovers and deployment of scientific instruments. The instruments and methods applied are described herein.

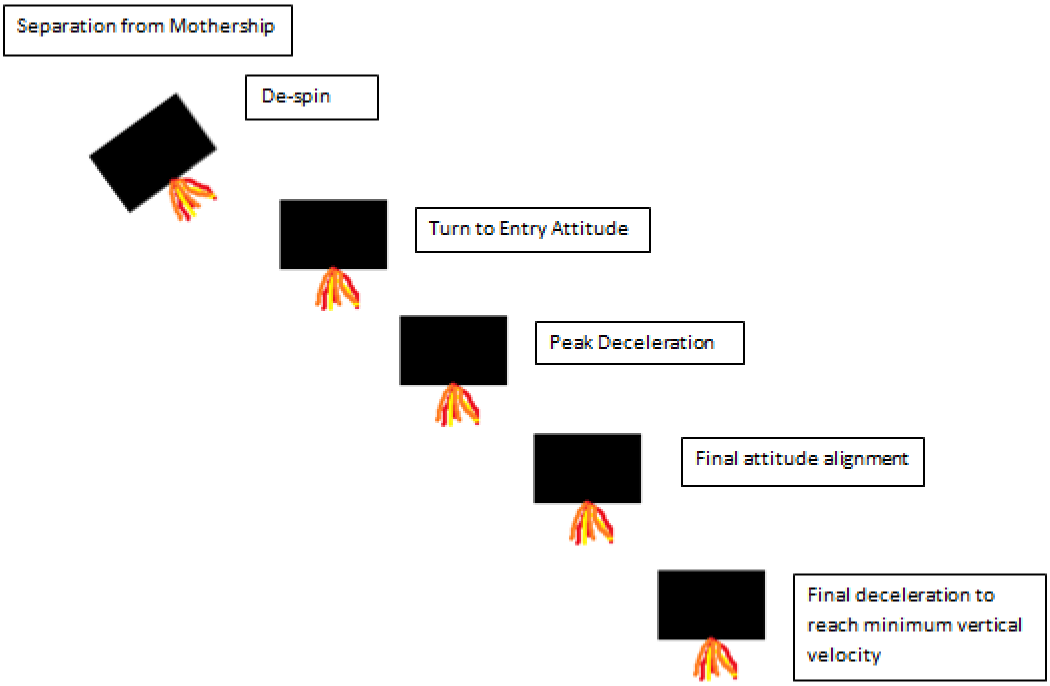
4.7.1 Mothership GNC

The Mothership orbiter will be equipped for navigation for trans-lunar injection (TLI), orbital maintenance, and attitude control for station-keeping. Since data will need to be transmitted to the satellite only when the Mothership is overhead the LunarBuses, station keeping requirements are minimal. A hypergolic ACS propulsion system using 16 Vernier thrusters, two on each corner of the orbiter, will be used for attitude control. Vernier thrusters have been used for attitude control on many different satellites due to their high reliability. A device such as a reaction wheel or control moment gyroscope (CMG) was ruled out because the station keeping requirements are minimal so that the added mass and power requirements were not advantageous. CMG's are also subject to singularities, meaning another attitude control system would likely be required, such as Vernier thrusters, for reliability. For orbit and attitude determination, multiple systems will be implemented for redundancy including two Moog Coarse Sun Sensors, two ASTRO APS star trackers, and two three-axis IMUs.

4.7.2 LunarBus GNC

Control of the LunarBus must include aspects of attitude and altitude control using a three axis control technique. Based on the moments of inertia from the structural design, thrust limits will be created based on the locations of ACS thrusters on the craft to maintain attitude control. Each LunarBus will be equipped with two ASTRO APS star trackers and two three-axis IMUs. Similar to the Dawn mission, a laser altimeter will be used to accurately determine altitude from the lunar surface. After separating from the Mothership, the LunarBus will de-spin and orient itself to proper attitude, then perform a peak deceleration maneuver near the surface, followed by a final attitude adjustment and then a final deceleration maneuver to reach ideally zero velocity at impact. Figure 19 shows a LunarBus in descent.

Figure 19: LunarBus Descent Stage



Descent control will handled by one gimballed AJ10-190 engine one the bottom of the LunarBus with a gimbal angle of ±6°. Ideally, a maximum of three burns will be needed for a controlled descent to minimize fuel consumption and produce a total ΔV of 778 m/s. Attitude control will be handled by eight Moog 5 pound-force ACS thrusters located on each top corner of the lander. Using the side mounted GPR, the LunarBus will analyze the crater to determine a safe, level landing zone free of large obstructions and adjust trajectory accordingly. Once on the surface, the LunarBus will deploy the ramp for the rovers and direct an antenna to transmit data to the Mothership when necessary. The payload will remain on the Moon, so relaunch is not considered.

4.7.3 MoonCube GNC

The MoonCube rovers will navigate by using an algorithm designed to explore the craters while using their GPR in an evenly dispersed spiral fashion to maximize coverage. The MoonCubes will need to be capable of basic lateral movement and turning using two front wheels. The rovers will deploy a drill to take regolith samples and analyze it using the spectrometer as they detect evidence of water from their GPR. The rovers will determine position using an IMU and a transponder communicating with its respective LunarBus to provide a real-time map of all other MoonCubes.

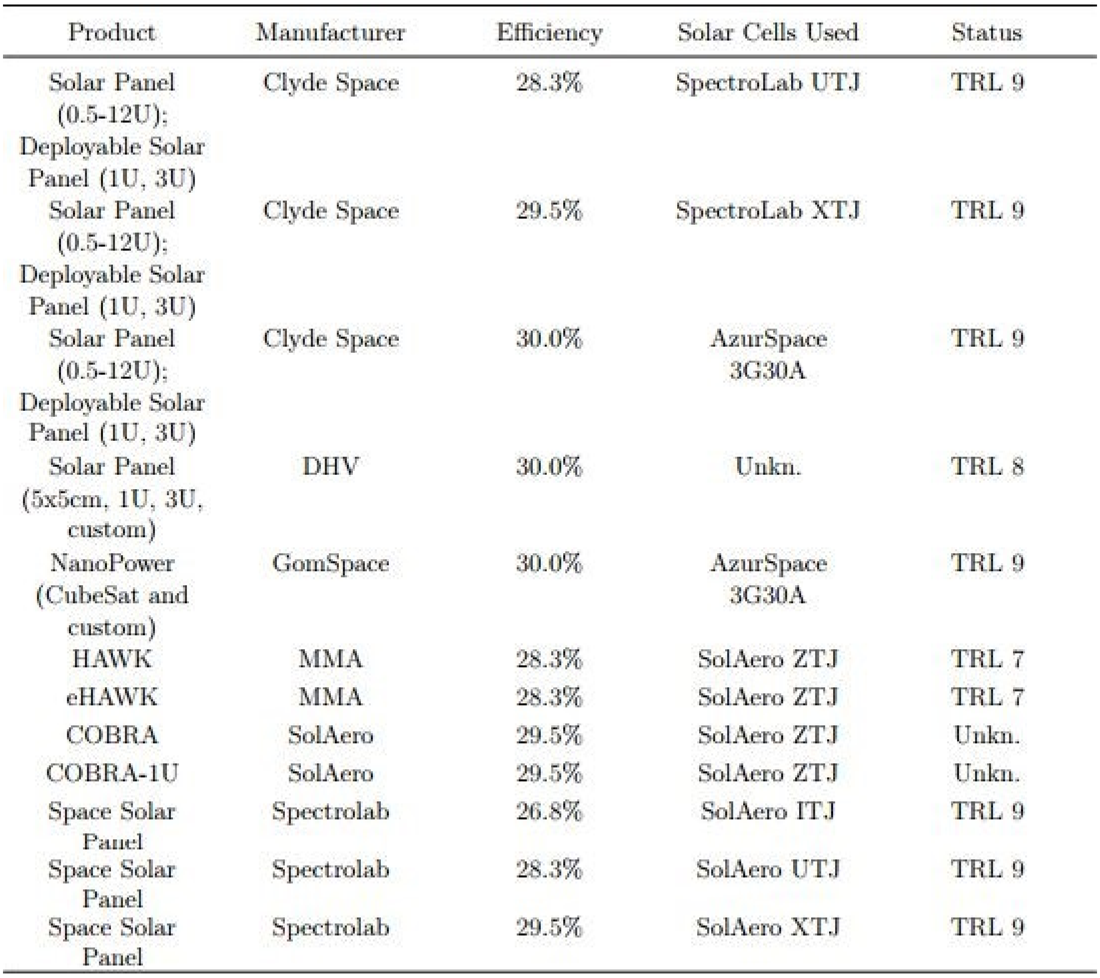
4.8 Power

The power subsystem is split between the Mothership, LunarBus, and MoonCubes. The power subsystem is required to supply and direct electrical power within each craft based on status of the mission.

4.8.1 Mothership Power

The Mothership will be powered by solar arrays supported by a secondary battery bank. The secondary bank will be space rated rechargeable Clyde Space Li-Polymer with an energy density of 150 W h $\text{kg}^{-}1$ [40]. The benefit of using Clyde Space batteries is that they have their own thermal control system that keeps the battery operating at 0 °C. Solar arrays are a reliable, cost efficient means of powering any sun-exposed system. The purpose of the battery bank is to store power for use in periods where the Mothership is not exposed to sunlight. Clyde Space is the manufacturer

Figure 20: Solar Panel Trade Study



Product	Manufacturer	Efficiency	Solar Cells Used	Status
Solar Panel (0.5-12U); Deployable Solar Panel (1U, 3U)	Clyde Space	28.3%	SpectroLab UTJ	TRL 9
Solar Panel (0.5-12U); Deployable Solar Panel (1U, 3U)	Clyde Space	29.5%	SpectroLab XTJ	TRL 9
Solar Panel (0.5-12U); Deployable Solar Panel (1U, 3U)	Clyde Space	30.0%	AzurSpace 3G30A	TRL 9
Solar Panel (5x5cm, 1U, 3U, custom)	DHV	30.0%	Unkn.	TRL 8
NanoPower (CubeSat and custom)	GomSpace	30.0%	AzurSpace 3G30A	TRL 9
HAWK	MMA	28.3%	SolAero ZTJ	TRL 7
eHAWK	MMA	28.3%	SolAero ZTJ	TRL 7
COBRA	SolAero	29.5%	SolAero ZTJ	Unkn.
COBRA-1U	SolAero	29.5%	SolAero ZTJ	Unkn.
Space Solar Panel	Spectrolab	26.8%	SolAero ITJ	TRL 9
Space Solar Panel	Spectrolab	28.3%	SolAero UTJ	TRL 9
Space Solar Panel	Spectrolab	29.5%	SolAero XTJ	TRL 9

Information retrieved from [28].

that will be contracted for solar arrays as they have a long standing heritage with small spacecrafts [40]. The solar arrays have 30% efficiency as it can be seen in Figure 20.

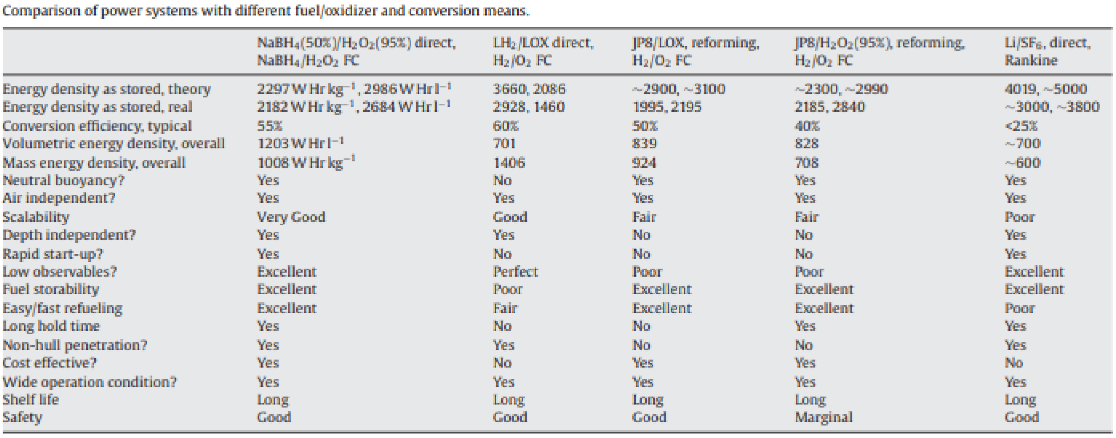
4.8.2 LunarBus Power

Unlike the Mothership, LunarBuses will be equipped with hydrogen-peroxide-based fuel cells (H_2O_2), which will provide an energy density of 2728 Watt hours per kilogram. This high energy density allows constant data processing and transmission over the course of the mission, greatly extending the overall lifespan of the MoonCubes. Fuel cells produce an electric current by passing hydrogen atoms through an anode, then combining the ionized hydrogen atoms with oxygen atoms at the cathode. The process results in electricity and water as byproducts. At the projected consumption of 61 Watts, less than 4 kg of fuel is needed to meet the 7 day minimum lifetime functional requirement.

4.8.3 MoonCube Power

MoonCubes will be powered by hydrogen-peroxide-based fuel cells (H_2O_2), which will provide an energy density of approximately 2700 Watt hours per kilogram [40]. These cells can be rescaled based on changing power requirements. Fuel cells will need to be further developed to make it more specific to the space application. The benefit of using fuel cells compared to traditional primary batteries is the high energy density. Because the MoonCubes will operate on scalable fuel cells, the mission operational life can be drastically increased without adding significant mass.

Figure 21: Fuel Cell Trade Study



Comparison of power systems with different fuel/oxidizer and conversion means.

	$NaBH_4$(50%)/H_2O_2(95%) direct, $NaBH_4/H_2O_2$ FC	LH_2/LOX direct, H_2/O_2 FC	JP8/LOX, reforming, H_2/O_2 FC	JP8/H_2O_2(95%), reforming, H_2/O_2 FC	Li/SF_6, direct, Rankine
Energy density as stored, theory	2297 W Hr kg^{-1}, 2986 W Hr l^{-1}	3660, 2086	~2900, ~3100	~2300, ~2990	4019, ~5000
Energy density as stored, real	2182 W Hr kg^{-1}, 2684 W Hr l^{-1}	2928, 1460	1995, 2195	2185, 2840	~3000, ~3800
Conversion efficiency, typical	55%	60%	50%	40%	<25%
Volumetric energy density, overall	1203 W Hr l^{-1}	701	839	828	~700
Mass energy density, overall	1008 W Hr kg^{-1}	1406	924	708	~600
Neutral buoyancy?	Yes	No	Yes	Yes	Yes
Air independent?	Yes	Yes	Yes	Yes	Yes
Scalability	Very Good	Good	Fair	Fair	Poor
Depth independent?	Yes	Yes	No	No	Yes
Rapid start-up?	Yes	No	No	No	Yes
Low observables?	Excellent	Perfect	Poor	Poor	Excellent
Fuel storability	Excellent	Poor	Excellent	Excellent	Excellent
Easy/fast refueling	Excellent	Fair	Excellent	Excellent	Poor
Long hold time	Yes	No	No	Yes	Yes
Non-hull penetration?	Yes	Yes	No	No	Yes
Cost effective?	Yes	No	Yes	Yes	No
Wide operation condition?	Yes	Yes	Yes	Yes	Yes
Shelf life	Long	Long	Long	Long	Long
Safety	Good	Good	Good	Marginal	Good

Information retrieved from [41].

Shown in Figure 21, hydrogen peroxide fuel cells are 55% energy efficient and very good at scalability. They, also, are able to hold the charge for a long time which is beneficial for mission success. Since there will be 306 needed to produce, the fuel cells will also be very cost effective [41]. Overall, fuel cell is better application for MoonCubes due to their high energy demand and the durability required to operate in such harsh conditions on the lunar surface.

In order to fulfill functional requirements, MoonCubes are required to operate for a minimum of 72 hours; at a total power consumption of 6120 Watts, 5 Kg of fuel mass is required aboard the MoonCubes.

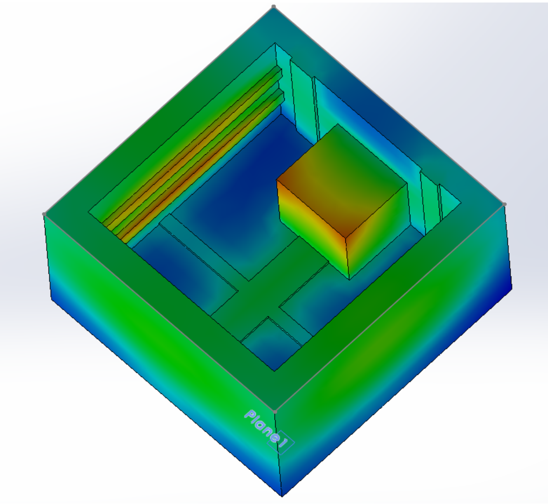
4.9 Thermal Control

The thermal subsystem ensures that the Mothership, LunarBus, and MoonCubes are able to operate within their required temperature ranges through thermal regulation. Environmental conditions of the lunar craters provide a substantial challenge. LunarBuses and MoonCubes will have to operate in temperatures as low as -238° C, as indicated in data provided by the Diviner Lunar Radiometer aboard NASA's Lunar Reconnaissance Orbiter [38].

4.9.1 Mothership TCS

The Mothership will be constantly exposed to solar radiation. Solar radiation causes rapid heating to the exposed surface, which can lead to a high temperature gradient across the spacecraft. Such a temperature gradient can cause deformation resulting in mission failure. The Mothership will be equipped with heat piping, louvers, and thermal control coating: heat piping distributes heat through a craft by conduction, louvers transition between reflective and absorptive modes depending on exposure, and thermal control coating utilizes high emissivity to reflect incident radiation and reflect waste heat. The batteries selected from Clyde Space have an onboard thermal control system that will maintain battery temperatures at 0 °C [15]. The projected temperature distribution of the Mothership can be seen in Figure 22.

Figure 22: Mothership Temperature Distribution

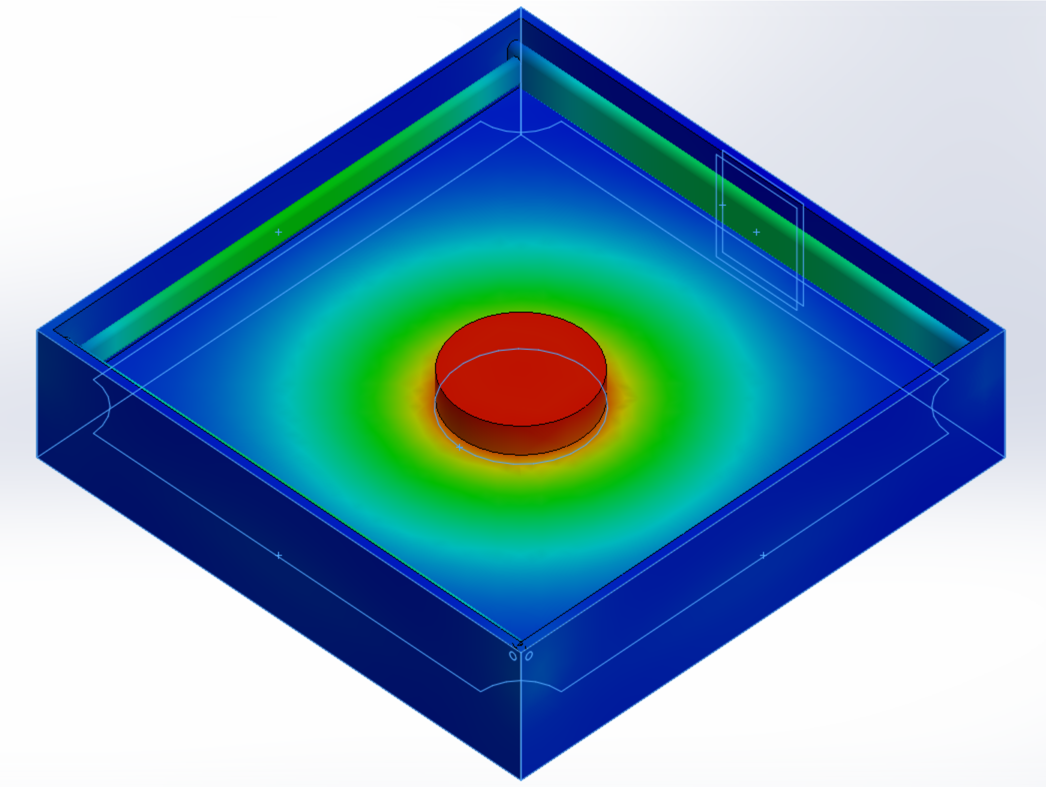


4.9.2 LunarBus TCS

Since the LunarBuses will house a hydrogen fuel cell, there will be passive heat pipes that will utilize waste heat from the fuel cell to aid in maintaining operating temperatures while keeping the fuel cell temperatures steady. In addition, LunarBuses will be equipped with thermal louvers to let excess heat radiate outwards. The LunarBus thermal system will be built with the same concerns as the MoonCubes. In order to maintain maximum power in the MoonCubes until deployment, the LunarBuses must fulfill the role of keeping their payloads within operating temperature. This will be achieved through electric heaters that will turn on once deployed from the Mothership. The projected LunarBus temperature distribution can be seen in Figure 23.

The thermal control system will need to meet the functional requirements in the area of performance and survivability. All three, the Mothership, LunarBuses, and MoonCubes, will need to survive and operate in harsh lunar environment where temperatures range -238 °C.

Figure 23: LunarBus Temperature Distribution



4.9.3 MoonCube TCS

MoonCubes will be internally packed with multi-layer insulation (MLI). MLI is a radiation transfer barrier composed of multiple layers of reflectors. No single reflector can provide 100 percent reflection of incident radiation, so by joining multiple layers together, a near perfect barrier can be created. There are no concerns for heat loss by conduction or convection, as there is no lunar atmosphere. Waste heat from the fuel cells and electronics aboard the MoonCubes will be distributed by heat piping.

Table 4: Inner Multi-Layer Insulation

Material	**Beta Cloth**	**Reinforced Tedlar**	**Kapton**	**Backed Teflon**	**Coated and Backed Teflon**
Temperature Range (°C)	< 204	-72 - 107	-73 - 65	-184 - 150	-73 - 65
Weight (g/cm^2)	0.0237	N/A	0.0036	0.0028 - 0.055	0.011 - 0.027
Emittance	0.8	0.8	0.5 - 0.81	0.40 - 0.85	0.6 - 0.75

Information retrieved from [39].

Analysis of available inner layers listed in Table 4 shows that backed teflon is the best option for our mission requirements, having the most favourable temperature range for our mission, as well as high in-class emittance at higher thicknesses.

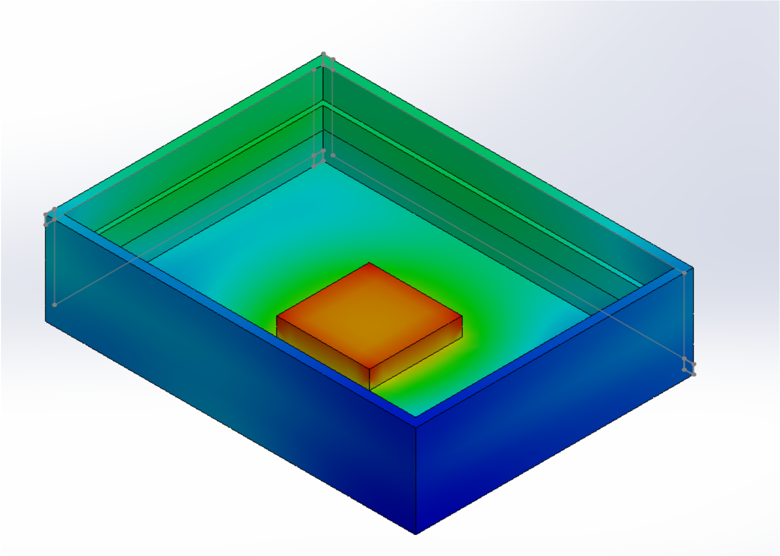
Table 5: Reflector MLI Layer Options

Material	**Aluminized Kapton**	**Goldized Kapton**	**Aluminized Mylar**	**Polyester**	**Teflon**
Temperature Range (°C)	-250 - 288	-250 - 288	-250 - 98	> 260	> 260
Weight (g/cm^2)	0.0011 - 0.019	0.011 - 0.019	0.0007 - 0.0175	N/A	N/A
Thickness (mm)	0.0076 - 0.127	0.0076 - 0.127	0.0051 - 0.127	N/A	N/A
Emittance	0.05	0.04	0.5	< 0.4	< 0.04

Information retrieved from [39].

While aluminized kapton, goldized kapton, and aluminized mylar all possess required properties for the mission, it was decided that aluminized mylar would be utilized due to it likely not experiencing high temperatures and having the lowest weight in its class. The projected temperature distribution of the MoonCubes can be seen in Figure 24.

Figure 24: MoonCube Temperature Distribution



4.10 Payload & Scientific Instruments

The payload subsystem is composed of a swarm of simple minded rovers called MoonCubes. Produced in quantity and with cubesat specifications, these MoonCubes will provide an efficient and cost effective way to rapidly prospect lunar craters. Unlike previous planetary rover missions like Mars Exploration Rover whose mission lives are measured in years, MoonCubes will only be designed to operate on the order of days. They will make up for their limited lifespan by using a swarm architecture. This was done due to the limitations imposed by the geometry of lunar craters. Due to the depth, temperature, permanent shadow from the sun, and large size of these craters, traditional rover designs would not be effective. The large number of MoonCubes offers redundancy in case one gets stuck or tipped, which is relatively likely in a crater with an unknown surface geometry.

4.10.1 LunarBuses

Carried to the Moon as an internal payload, MoonCubes will be transported to the surface using LunarBuses. Each LunarBus functions similarly to Curiosity's Skycrane as it safely delivers MoonCubes to the lunar surface and then acts as a command and control hub. The LunarBus will be preloaded with its payload on Earth and will deploy its MoonCubes once on the surface of the Moon. LunarBuses will create a network, the Lunar Exploration Network (LEN) before MoonCube deployment. LEN will allow LunarBuses to receive data and coordinate each of their respective MoonCubes within the swarm. This will allow a quick and efficient reconnaissance of each crater.

During the descent phase, the LunarBus will utilize a Side-Mounted ground penetrating radar (SMR), which will be a large scale version of Mars 2020's RIMFAX. As a LunarBus gets closer to the surface of the crater, the resolution of the SMR will become more refined. Using this data, the LunarBus will steer itself towards a landing site near an area dense with water deposits.

4.10.2 MoonCubes

A MoonCube is a 12U sized wheeled rover that uses swarm technology to quickly and effectively prospect a lunar crater. Each MoonCube will be simple minded and map near-surface ice and mineral deposits using a GPR system. MoonCubes will be equipped with a derivative of the Radar Imager for Mars' Subsurface Experiment (RIMFAX), which will be used on the Mars 2020 rover [24]. The general specifications for RIMFAX are shown below in Table 7.

Table 6: RIMFAX & SMR General Specifications

Instrument Name	**Mass**	**Power Required**	**Frequency**	**Vertical Resolution**	**Penetration Depth**	**Measurement Interval**	**Volume**
RIMFAX	3 kg	5 - 10 W	150 - 1200 MHz	15 - 30 cm	>10 m	10 cm	196x120x66 mm
SMR	6 kg	20 - 40 W	150 - 1200 MHz	30 - 50 cm	>10 m	N/A cm	392x240x66 mm

Information retrieved from [24].

A key design detail about RIMFAX is its unique bowtie configuration, which allows a miniaturized GPR to both receive and transceive signals at the same time - improving its resolution and data collection rate. RIMFAX's design was chosen as it is the only design currently in development or deployed that will both fit under a MoonCube and is within our power constraints.

A laser spectrometer, an associated camera, and drill will be incorporated into the structure of each MoonCube. The Lunar Camera, Laser Spectrometer and Drill (LCLD) assembly will be derived from the Mars Science Laboratory's ChemCam [25]. LCLD will be mounted internally on the lower portion of a MoonCube's chassis. Once a deposit has been located, a telescoping drill will bore a hole 2 cm wide by 1.5 m in depth. As material is extracted, an infrared laser will vaporize it, and the camera will then identify the material from the resultant plasma. LCLD will also be usable on surface targets directly under the rover without the use of a drill.

The payload subsystem allows the functional requirements of identifying concentrations of a minimum of 5% water mass at a depth up to 10m, and the collection of data to be uploaded to NEN. The use of individual MoonCubes and LunarBuses enables the functional requirement of mapping 600 square kilometers per crater. The MoonCube collection techniques also allow the prospecting of materials other than water.

5 Conclusion

The Flat Moon Society has been tasked to lead an exploration mission to the Moon in search of water. Evidence of water could lead to construction of a Lunar base able to support human life as well as serve as a refueling station for deep space missions. The mission will explore two specific craters that show the most promising chances of finding water. The craters' locations will be determined by the Lunar Flashlight and Lunar Icecube missions and will likely be located on the south pole of the moon in areas of permanent darkness.The entire budget of the mission must be within $500 million USD.

The concept of operations consists of three primary phases: (1) Transport, (2) Deployment, and (3) Operation. The mission will be carried out by three different components: the Mothership, LunarBuses, and MoonCubes. The launch will happen at Cape Canaveral Air Force Station in Florida in 2024 and will use SpaceX's Falcon Heavy rocket to place the Mothership into TransLunar Injection. From there, the Mothership will orbit the Moon in a polar orbit. Once in position over the crater, LunarBuses will detatch from the Mothership and transport the prepackaged MoonCubes to the surface of the crater, where the MoonCubes will scatter and carry out their missions. The MoonCubes will analyze the crater over a period of three days in a swarm fashion and relay all data to their respective LunarBuses, which will then transmit data to the Mothership when it passes overhead. The LunarBuses will also act as command and control centers, managing the MoonCube swarm. The Mothership will compact the data with its onboard VMC and uplink it to the Near Earth Network.

MoonCubes will be powered by Lithium Ion primary batteries. LunarBuses will be powered through the use of a hydrogen fuel cells. The thermal control subsystem will work with the power subsystem to regulate temperature through insulation, electric heaters, and louvers. The power subsystem will need to account for added energy consumption from the harsh range of operating temperatures. In terms of propulsion, the mothership will have a single hypergolic main engine with sixteen hypergolic attitude control thrusters. In addition, the LunarBuses will have a single hypergolic gimbaled rocket engine and eight hypergolic ACS thrusters mounted on its upper portion. The structures subsystem for the Mothership, LunarBus, and MoonCubes will utilize both carbon fiber reinforced polymer and aluminum to minimize weight and to maximize structural strength.

This plan will fulfill the mission requirements put forth by the AIAA competition. Successfully detecting water deposits on the Moon could open the door to creating a refueling station on the moon, accelerating humankind's space exploration.

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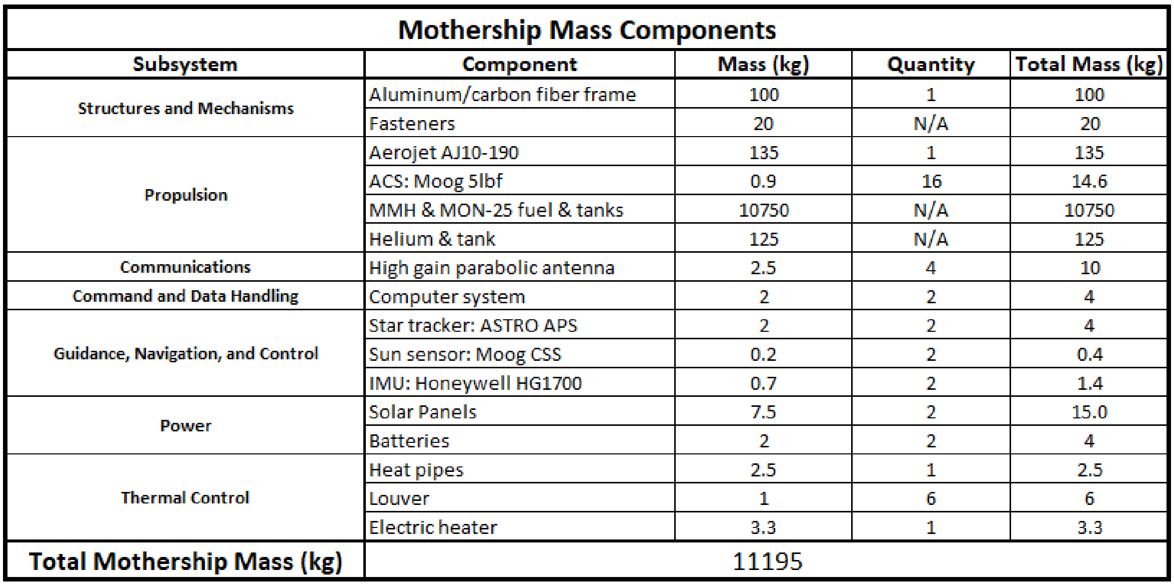
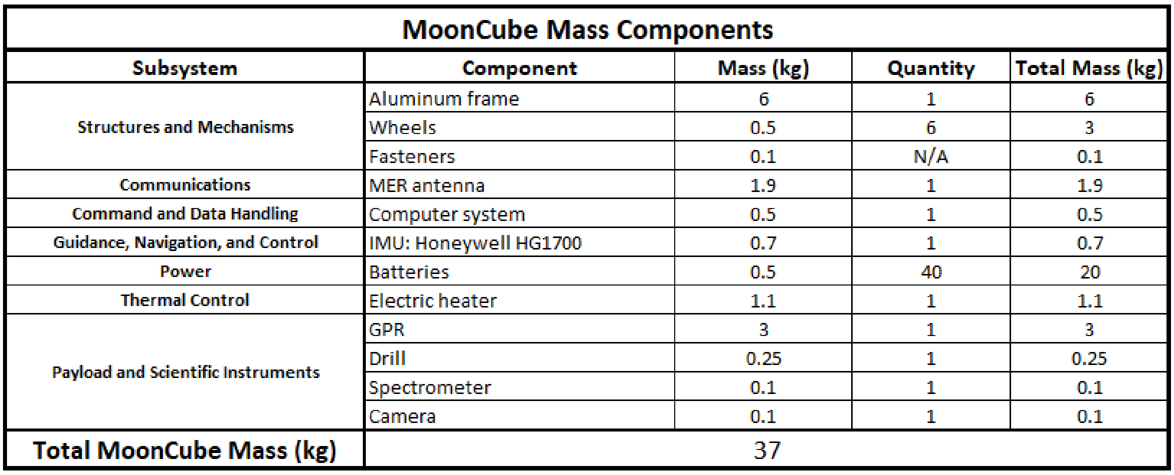
7 Appendices

7.1 Mass Components



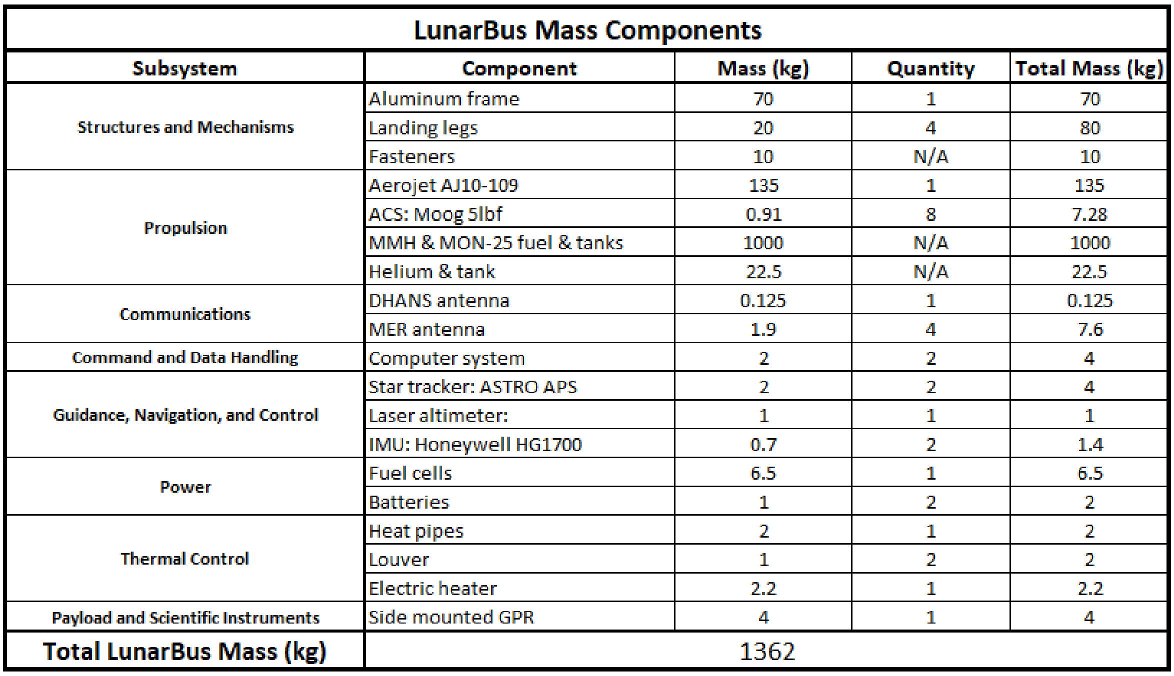
Mothership Mass Components

Subsystem	Component	Mass (kg)	Quantity	Total Mass (kg)
Structures and Mechanisms	Aluminum/carbon fiber frame	100	1	100
	Fasteners	20	N/A	20
Propulsion	Aerojet AJ10-190	135	1	135
	ACS: Moog 5lbf	0.9	16	14.6
	MMH & MON-25 fuel & tanks	10750	N/A	10750
	Helium & tank	125	N/A	125
Communications	High gain parabolic antenna	2.5	4	10
Command and Data Handling	Computer system	2	2	4
Guidance, Navigation, and Control	Star tracker: ASTRO APS	2	2	4
	Sun sensor: Moog CSS	0.2	2	0.4
	IMU: Honeywell HG1700	0.7	2	1.4
Power	Solar Panels	7.5	2	15.0
	Batteries	2	2	4
Thermal Control	Heat pipes	2.5	1	2.5
	Louver	1	6	6
	Electric heater	3.3	1	3.3
Total Mothership Mass (kg)	11195			



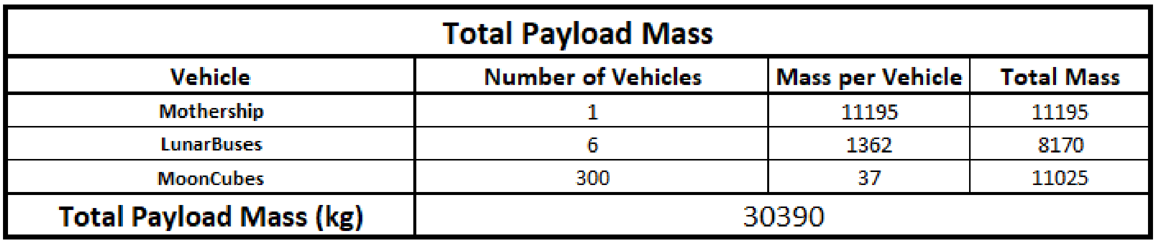
MoonCube Mass Components

Subsystem	Component	Mass (kg)	Quantity	Total Mass (kg)
Structures and Mechanisms	Aluminum frame	6	1	6
	Wheels	0.5	6	3
	Fasteners	0.1	N/A	0.1
Communications	MER antenna	1.9	1	1.9
Command and Data Handling	Computer system	0.5	1	0.5
Guidance, Navigation, and Control	IMU: Honeywell HG1700	0.7	1	0.7
Power	Batteries	0.5	40	20
Thermal Control	Electric heater	1.1	1	1.1
Payload and Scientific Instruments	GPR	3	1	3
	Drill	0.25	1	0.25
	Spectrometer	0.1	1	0.1
	Camera	0.1	1	0.1
Total MoonCube Mass (kg)	37			



LunarBus Mass Components

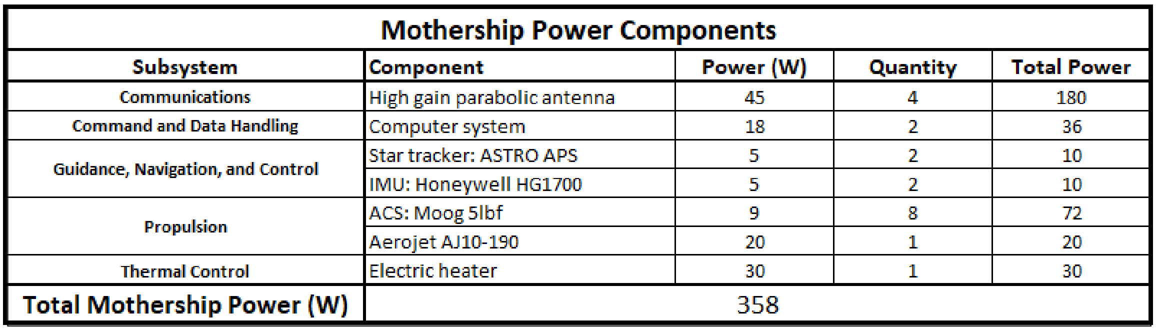
Subsystem	Component	Mass (kg)	Quantity	Total Mass (kg)
Structures and Mechanisms	Aluminum frame	70	1	70
	Landing legs	20	4	80
	Fasteners	10	N/A	10
Propulsion	Aerojet AJ10-109	135	1	135
	ACS: Moog 5lbf	0.91	8	7.28
	MMH & MON-25 fuel & tanks	1000	N/A	1000
	Helium & tank	22.5	N/A	22.5
Communications	DHANS antenna	0.125	1	0.125
	MER antenna	1.9	4	7.6
Command and Data Handling	Computer system	2	2	4
Guidance, Navigation, and Control	Star tracker: ASTRO APS	2	2	4
	Laser altimeter:	1	1	1
	IMU: Honeywell HG1700	0.7	2	1.4
Power	Fuel cells	6.5	1	6.5
	Batteries	1	2	2
Thermal Control	Heat pipes	2	1	2
	Louver	1	2	2
	Electric heater	2.2	1	2.2
Payload and Scientific Instruments	Side mounted GPR	4	1	4
Total LunarBus Mass (kg)	1362			



Total Payload Mass

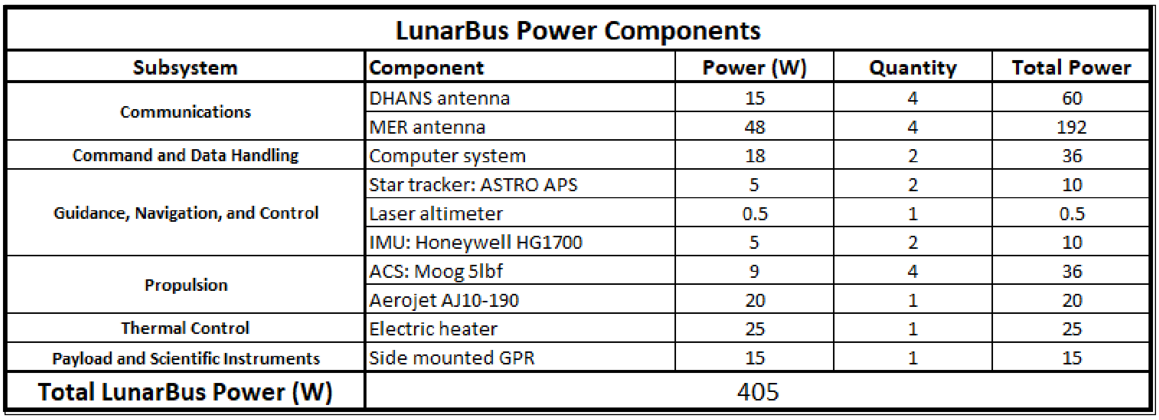
Vehicle	Number of Vehicles	Mass per Vehicle	Total Mass
Mothership	1	11195	11195
LunarBuses	6	1362	8170
MoonCubes	300	37	11025
Total Payload Mass (kg)	30390		

7.2 Power Components



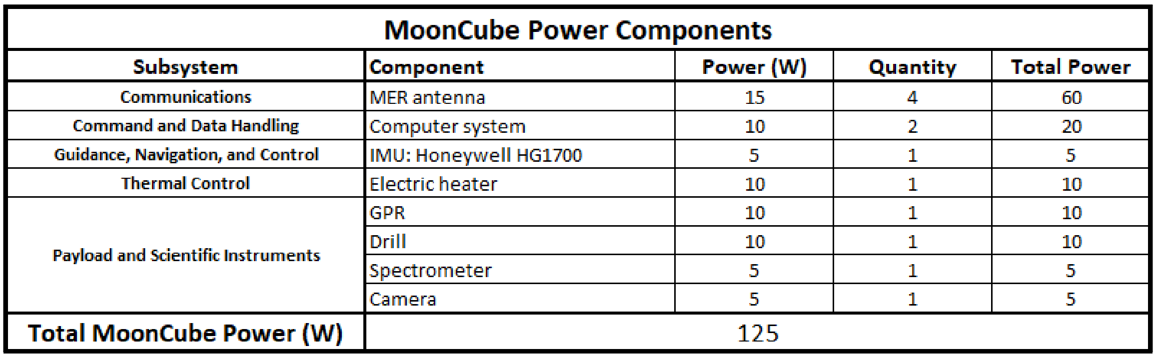
Mothership Power Components

Subsystem	Component	Power (W)	Quantity	Total Power
Communications	High gain parabolic antenna	45	4	180
Command and Data Handling	Computer system	18	2	36
Guidance, Navigation, and Control	Star tracker: ASTRO APS	5	2	10
	IMU: Honeywell HG1700	5	2	10
Propulsion	ACS: Moog 5lbf	9	8	72
	Aerojet AJ10-190	20	1	20
Thermal Control	Electric heater	30	1	30
Total Mothership Power (W)	358			



LunarBus Power Components

Subsystem	Component	Power (W)	Quantity	Total Power
Communications	DHANS antenna	15	4	60
	MER antenna	48	4	192
Command and Data Handling	Computer system	18	2	36
Guidance, Navigation, and Control	Star tracker: ASTRO APS	5	2	10
	Laser altimeter	0.5	1	0.5
	IMU: Honeywell HG1700	5	2	10
Propulsion	ACS: Moog 5lbf	9	4	36
	Aerojet AJ10-190	20	1	20
Thermal Control	Electric heater	25	1	25
Payload and Scientific Instruments	Side mounted GPR	15	1	15
Total LunarBus Power (W)	405			



MoonCube Power Components

Subsystem	Component	Power (W)	Quantity	Total Power
Communications	MER antenna	15	4	60
Command and Data Handling	Computer system	10	2	20
Guidance, Navigation, and Control	IMU: Honeywell HG1700	5	1	5
Thermal Control	Electric heater	10	1	10
Payload and Scientific Instruments	GPR	10	1	10
	Drill	10	1	10
	Spectrometer	5	1	5
	Camera	5	1	5
Total MoonCube Power (W)	125			

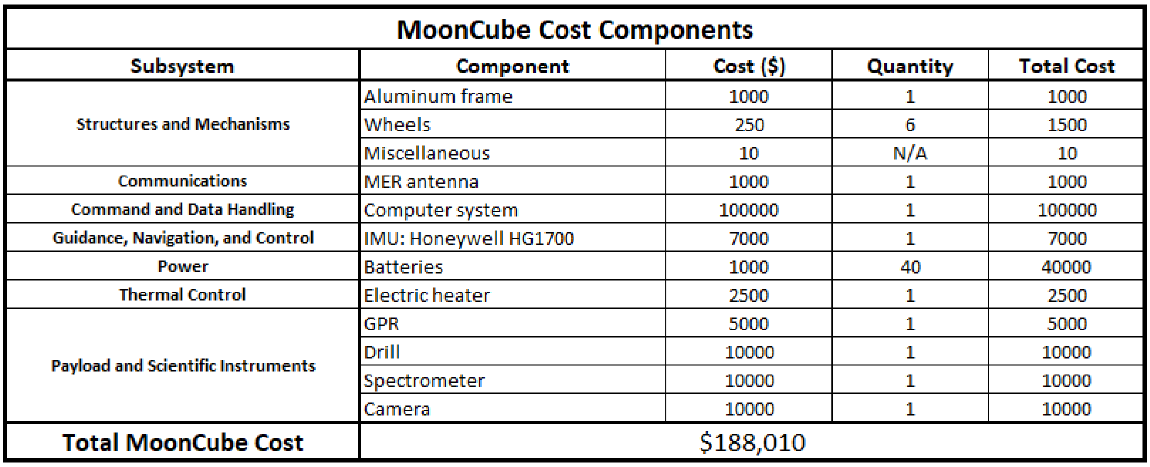
7.3 Total Cost

Mothership Cost Components

Subsystem	Component	Cost ($)	Quantity	Total Cost
Structures and Mechanisms	Aluminum/carbon fiber frame	25000	1	25000
	Fasteners	500	N/A	500
Propulsion	Aerojet AJ10-190	1000000	1	1000000
	ACS: Moog 5lbf	200000	16	3200000
	MMH & MON-25 fuel & tanks	3250000	N/A	3250000
	Helium & tank	25000	N/A	25000
Communications	High gain parabolic antenna	100000	4	400000
Command and Data Handling	Computer system	200000	2	400000
Guidance, Navigation, and Control	Star tracker: ASTRO APS	400000	2	800000
	Sun sensor: Moog CSS	55000	2	110000
	IMU: Honeywell HG1700	7000	2	14000
Power	Solar Panels	35000	2	70000
	Batteries	5000	2	10000
Thermal Control	Heat pipes	12000	1	12000
	Louver	7500	4	30000
	Electric heater	6000	1	6000
Total Mothership Cost ($)	$9,352,500			

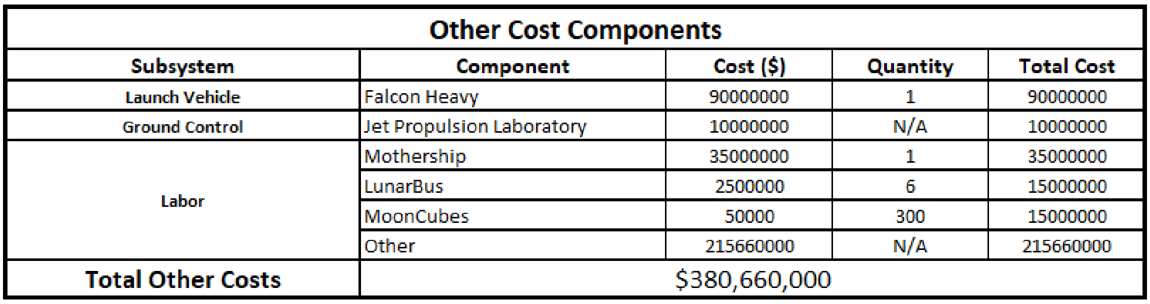
LunarBus Cost Components

Subsystem	Component	Cost ($)	Quantity	Total Cost
Structures and Mechanisms	Aluminum frame	10000	1	10000
	Landing legs	5000	4	20000
	Miscellaneous	500	N/A	500
Propulsion	Aerojet AJ10-190	1000000	1	1000000
	ACS: Moog 5lbf	200000	8	1600000
	MMH & MON-25 fuel & tanks	300000	N/A	300000
	Helium & tank	5000	N/A	5000
Communications	DHANS antenna	40000	1	40000
	MER antenna	1000	4	4000
Command and Data Handling	Computer system	200000	2	400000
Guidance, Navigation, and Control	Star tracker: ASTRO APS	400000	2	800000
	Laser altimeter	5000	1	5000
	IMU: Honeywell HG1700	7000	2	14000
Power	Fuel cells	275000	1	275000
	Batteries	1000	4	4000
Thermal Control	Heat pipes	17000	1	17000
	Louver	7500	2	15000
	Electric heater	4000	1	4000
Payload and Scientific Instruments	Side mounted GPR	10000	1	10000
Total LunarBus Cost	$4,523,500			



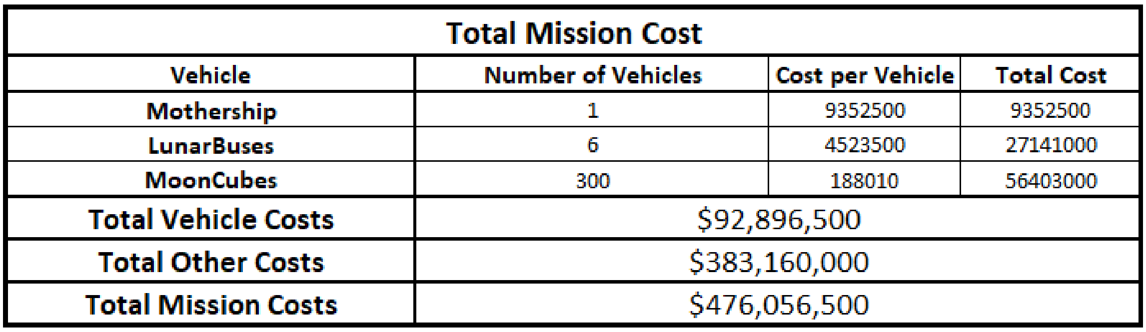
MoonCube Cost Components

Subsystem	Component	Cost ($)	Quantity	Total Cost
Structures and Mechanisms	Aluminum frame	1000	1	1000
	Wheels	250	6	1500
	Miscellaneous	10	N/A	10
Communications	MER antenna	1000	1	1000
Command and Data Handling	Computer system	100000	1	100000
Guidance, Navigation, and Control	IMU: Honeywell HG1700	7000	1	7000
Power	Batteries	1000	40	40000
Thermal Control	Electric heater	2500	1	2500
Payload and Scientific Instruments	GPR	5000	1	5000
	Drill	10000	1	10000
	Spectrometer	10000	1	10000
	Camera	10000	1	10000
Total MoonCube Cost	$188,010			



Other Cost Components

Subsystem	Component	Cost ($)	Quantity	Total Cost
Launch Vehicle	Falcon Heavy	90000000	1	90000000
Ground Control	Jet Propulsion Laboratory	10000000	N/A	10000000
Labor	Mothership	35000000	1	35000000
	LunarBus	2500000	6	15000000
	MoonCubes	50000	300	15000000
	Other	215660000	N/A	215660000
Total Other Costs	$380,660,000			



Total Mission Cost

Vehicle	Number of Vehicles	Cost per Vehicle	Total Cost
Mothership	1	9352500	9352500
LunarBuses	6	4523500	27141000
MoonCubes	300	188010	56403000
Total Vehicle Costs	$92,896,500		
Total Other Costs	$383,160,000		
Total Mission Costs	$476,056,500		

7.4 Link Budget

	Mothership to NEN	**NEN to Mothership**
$\frac{E_b}{N_o}_{dB,act}$	24.5 dB	6.50 dB
Transmitted Power (P)	24.5 W	0.029 W
Line Loss (L_l)	-1 dB	-1 dB
Transmitter Antenna Gain (G_t)	39.4 dB	52.4 dB
Space Loss (L_s)	-213.5 dB	-213.5 dB
Transmission Path Loss (L_a)	-0.100 dB	-0.100 dB
Receiving Antenna Gain (G_r)	52.3 dB	39.4 dB
System Noise Temperature (T_s)	27.9 dB	27.9 dB
Data Rate (R)	3.47 Mbps	256 kbps
Implementation Loss (L_i)	-2 dB	-2 dB

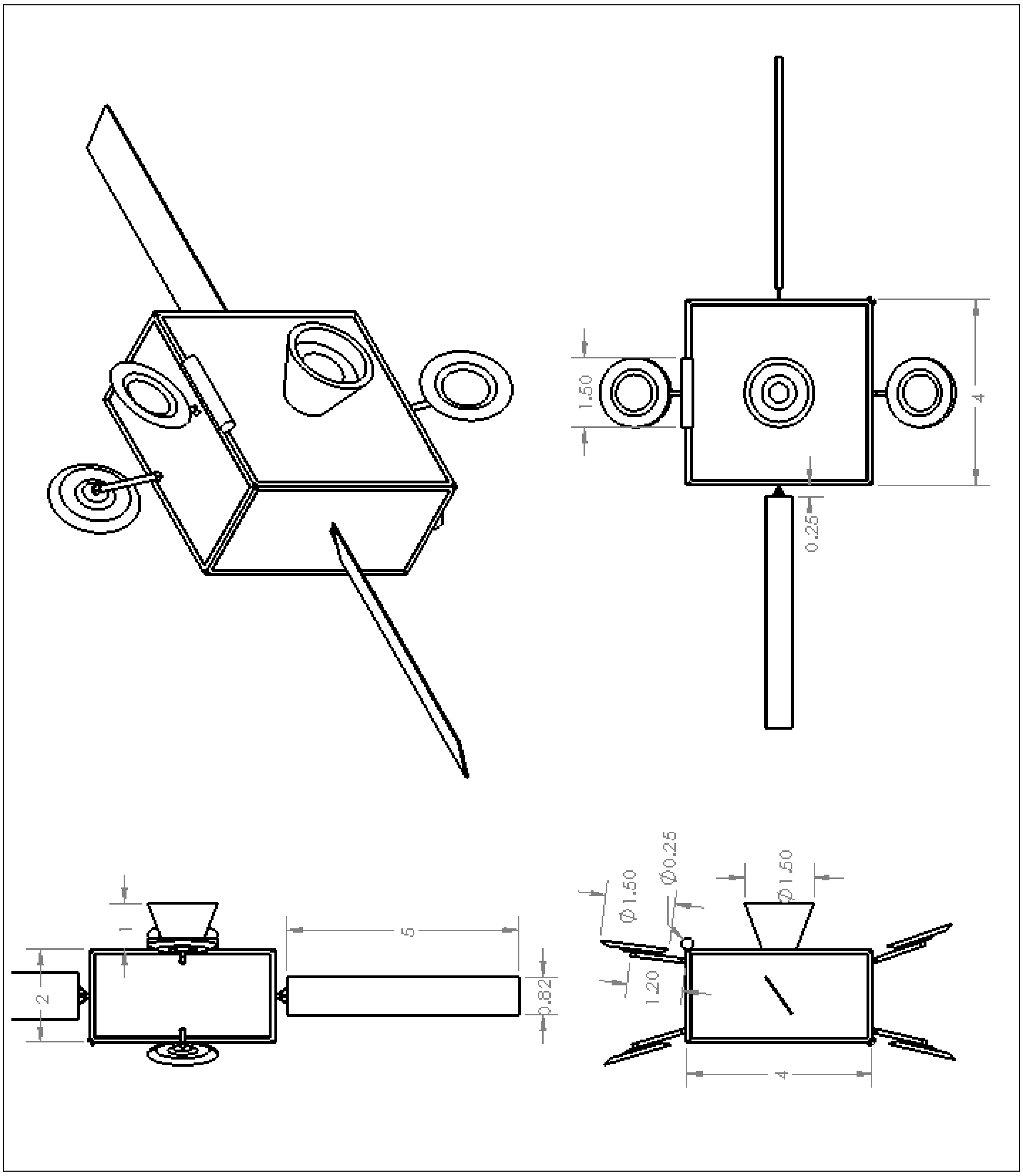
	Mothership to LunarBus
$\frac{E_b}{N_o}_{dB,act}$	24.5 dB
Transmitted Power (P)	2.27 W
Line Loss (L_l)	-1 dB
Transmitter Antenna Gain (G_t)	39.4 dB
Space Loss (L_s)	-188 dB
Transmission Path Loss (L_a)	-0.100 dB
Receiving Antenna Gain (G_r)	29.5 dB
System Noise Temperature (T_s)	27.9 dB
Data Rate (R)	5.77 Mbps
Implementation Loss (L_i)	-2 dB

	LunarBus to Mothership (MER)	**LunarBus to Mothership (DHANS)**
$\frac{E_b}{N_o}_{dB,act}$	24.5 dB	24.5 dB
Transmitted Power (P)	180 W	132.4 W
Line Loss (L_l)	-1 dB	-1 dB
Transmitter Antenna Gain (G_t)	11.84 dB	17.8 dB
Space Loss (L_s)	-184 dB	-184 dB
Transmission Path Loss (L_a)	-0.100 dB	-0.100 dB
Receiving Antenna Gain (G_r)	29.8 dB	29.9 dB
System Noise Temperature (T_s)	27.9 dB	27.9 dB
Data Rate (R)	230 kbps	5.77 Mbps
Implementation Loss (L_i)	-2 dB	-2 dB

	LunarBus to MoonCube	**MoonCube to LunarBus**
$\frac{E_b}{N_o}_{dB,act}$	24.5 dB	24.5 dB
Transmitted Power (P)	197 W	45 W
Line Loss (L_l)	-1 dB	-1 dB
Transmitter Antenna Gain (G_t)	23.8 dB	7.35 dB
Space Loss (L_s)	-101 dB	-101 dB
Transmission Path Loss (L_a)	-0.100 dB	-0.100 dB
Receiving Antenna Gain (G_r)	7.35 dB	23.8 dB
System Noise Temperature (T_s)	27.9 dB	27.9 dB
Data Rate (R)	1.8 Mbps	265 kbps
Implementation Loss (L_i)	-2 dB	-2 dB

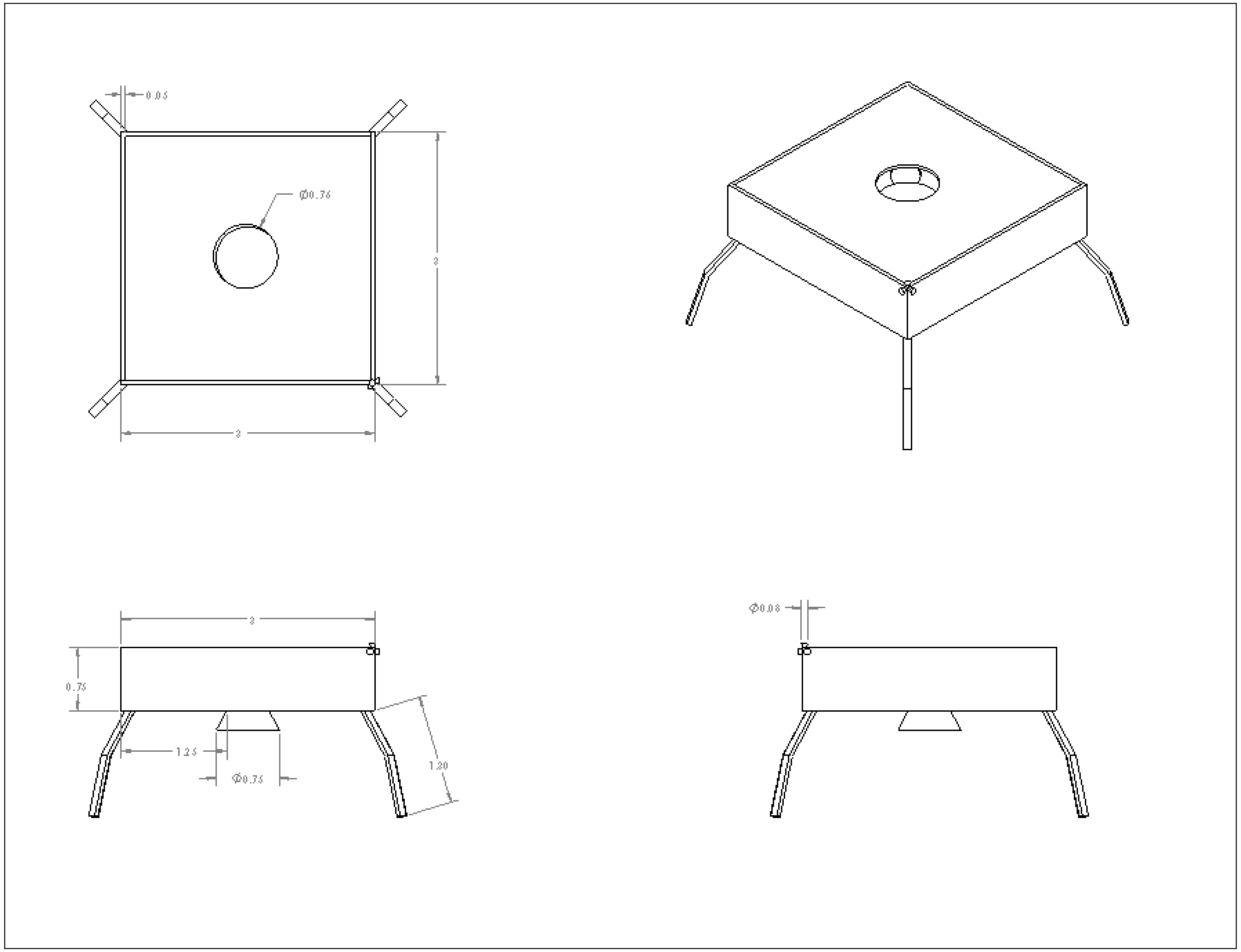
7.5 Vehicle Diagrams

The Mothership



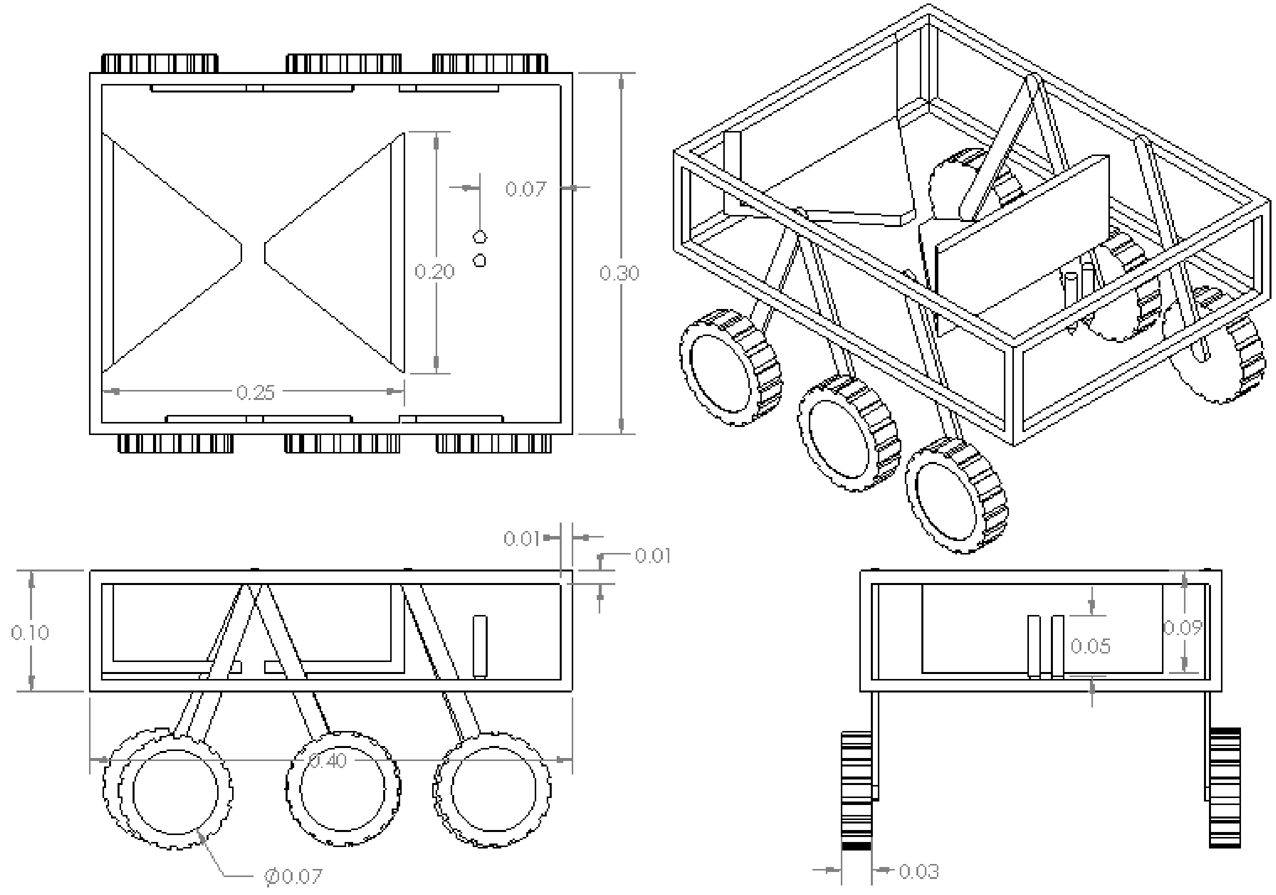
All dimensions in meters

The LunarBus



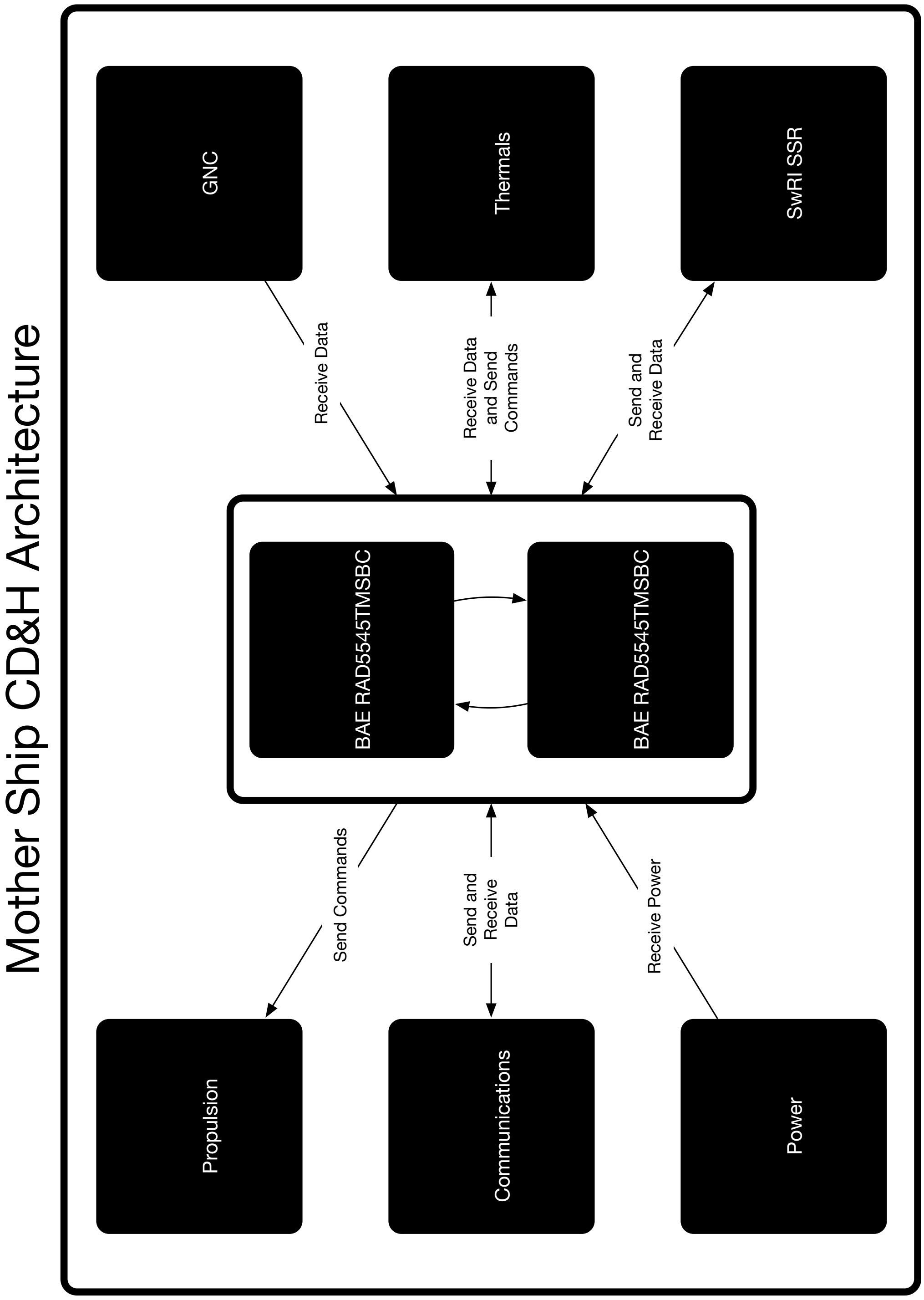
All dimensions in meters

The MoonCube

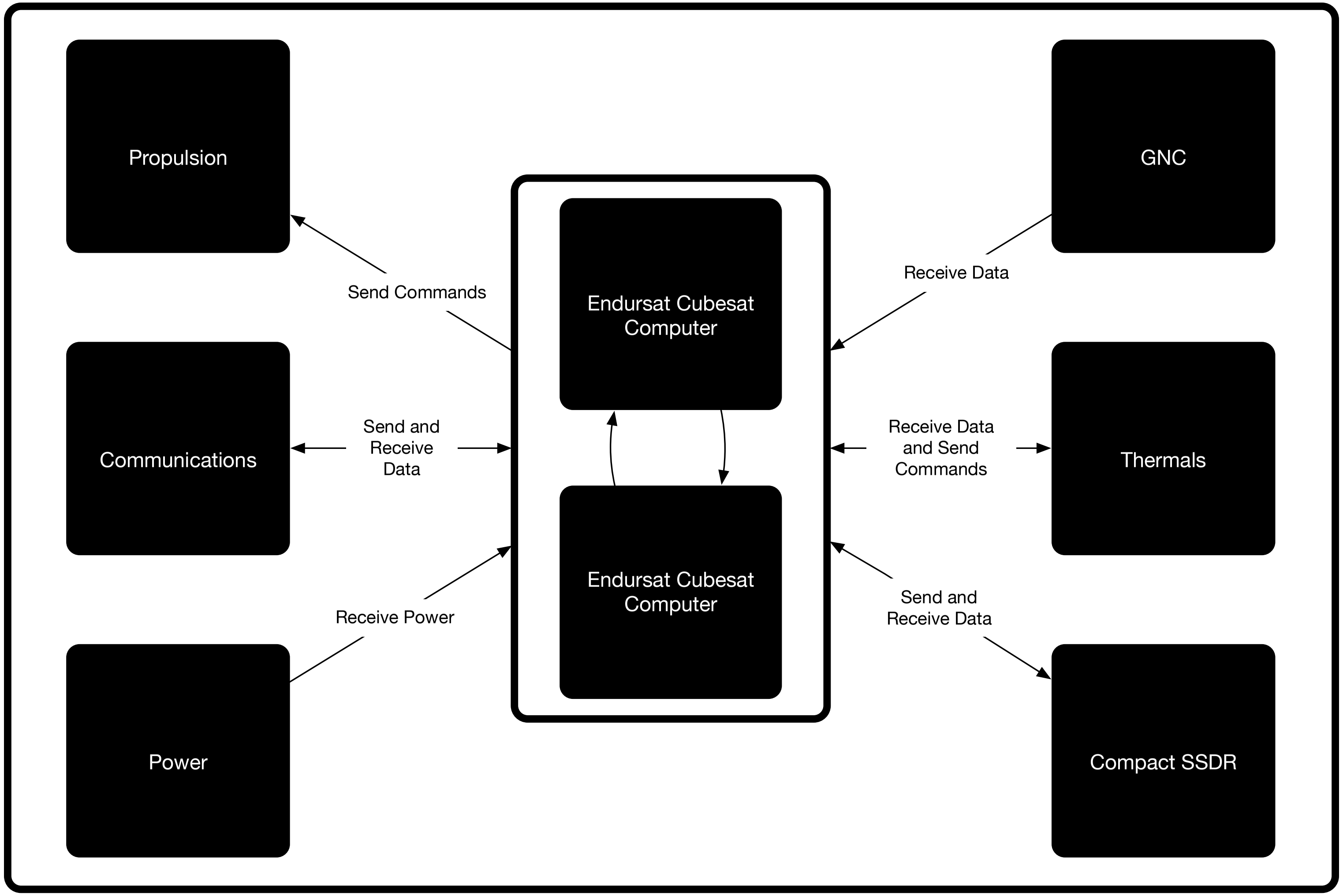


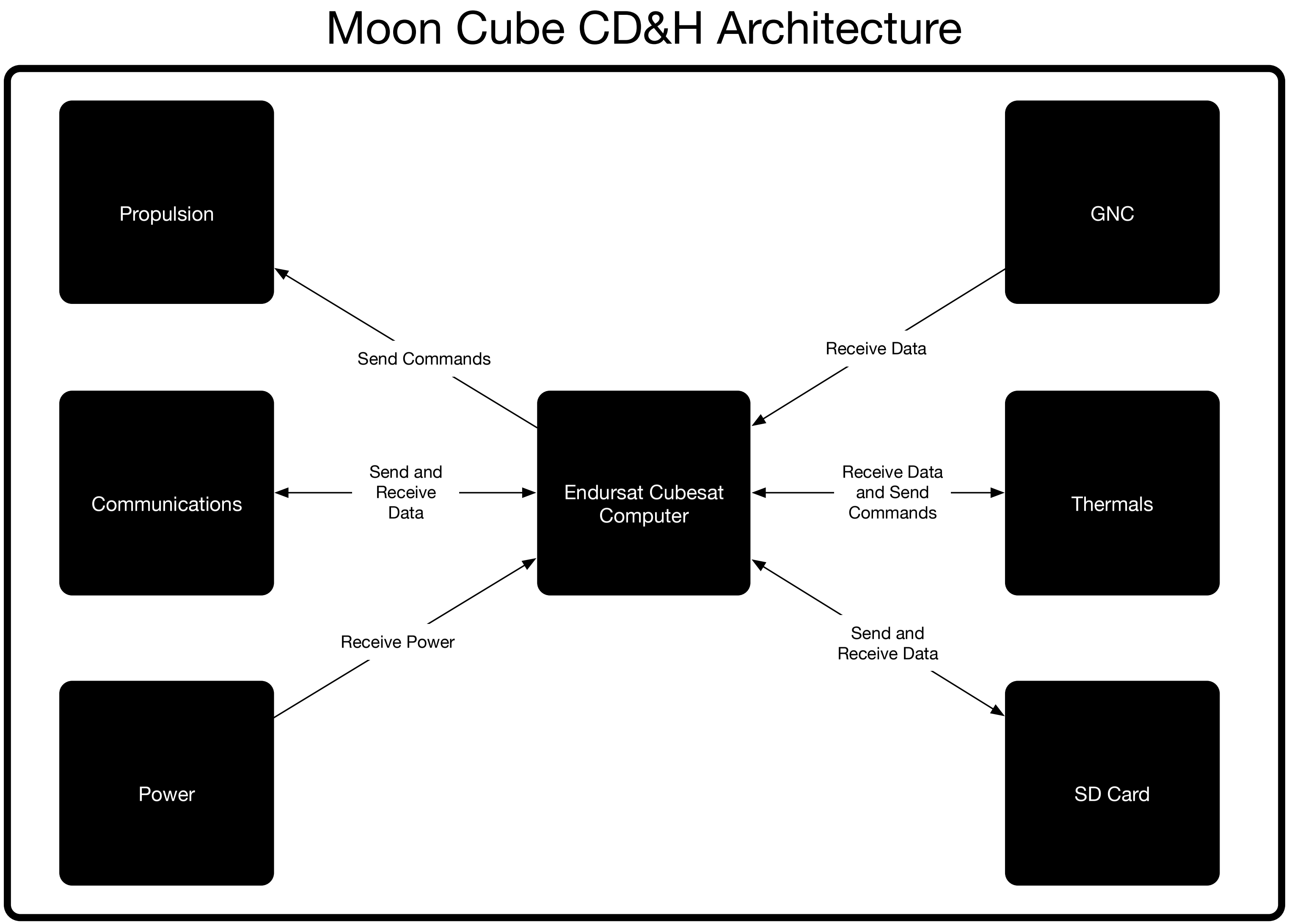
All dimensions in meters

7.6 C&DH Data Flow Diagrams



Lunar Bus CD&H Architecture




Moon Cube CD&H Architecture
Propulsion
GNC
Send Commands
Receive Data
Communications
Send and Receive Data
Endursat Cubesat Computer
Receive Data and Send Commands
Thermals
Receive Power
Send and Receive Data
Power
SD Card