Conceptual Design of a CubeSat-Based Lunar Rover Swarm Mission

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Abstract

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by Aysha Rehman

The advent of lunar exploration with the Artemis program is the basis of future missions to the Moon and Mars. With this boom in space exploration, the need for cost and time-effective reconnaissance missions is imperative to humanity's foray into further exploring our solar system. This paper covers a basic design outline of a potential CubeSat based rover swarm mission to the Moon. The CubeSat based body will provide an affordable, standardized form factor for use in rovers that can be sent to study the lunar surface and beyond. One landing site of interest is lava tubes or pits on the Moon that harbor a temperate climate, fit for human habitation. This paper outlines what such a mission might look like, and how a rover based on this criteria can be developed.

Acknowledgements

I'd like to acknowledge my family first and foremost for giving me the support and foundation to focus on school and pursue my dreams. All the discipline and values they instilled in me propelled me into the opportunities I have today, and my success is due in part to their love and patience. I would also like to acknowledge my friends, loved ones, professors and mentors who have encouraged me and shared the joys and struggles of my college experience, thank you for being a part of my life. Lastly, I would like to acknowledge my advisor Dr. Papadopoulos, mentor Marcus Murbach, and my colleagues at TechEdSat who have guided me and given me the skills I needed to grow professionally. Thank you all for your support, I couldn't have succeeded without you!

Nomenclature

Symbol	Definition	Units (SI)
U	CubeSat unit of volume, 10x10x10 cm	-------
W	Watts	W
Greek Symbols		
-------	-------	-------
Acronyms		
AI	Artificial Intelligence	-------
ALSEP	Apollo Lunar Surface Experiments Package	-------
ConOps	Concept of Operations	-------
COTS	Commercial off the shelf (Components)	-------
GNC	Guidance, navigation, and controls	-------
ISS	International Space Station	-------
NASA	National Aeronautics and Space Association	-------
NRHO	Near rectilinear halo orbit	-------
RTG	Radioisotope Thermoelectric Generator	-------
TechEdSat	Technology Education Satellite	-------
UCLA	University of California Los Angeles	-------

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Chapter 1
Introduction

1.1 Motivation

As humanity looks to expand colonization efforts to other planets, a renewed interest in crewed spaceflight has followed. Considering missions such as those outlined in the Artemis program, the first step to establishing human bases on other planets begins with a base on the moon. As outlined in the Artemis program timeline, the first mission to the moon is to launch in 2024 [1]. With such an ambitious schedule, the right tools must be utilized to efficiently survey and collect data on the moon's surface. Such data would aid in establishing ideal landing sites, a thorough analysis of possible building materials, and serve as a steppingstone for more comprehensive missions on other bodies such as Mars or Titan.

To lay down the groundwork for an adequate lunar base, further study of the lunar surface must be conducted by lunar rovers and satellites. Benefits to using rovers is that they allow for a broad collection of selective and intelligent observations [2]. Such rovers would be outfitted with tools and sensors that conduct a sweeping investigation of the lunar regolith, and atmospheric conditions including radiation. These factors are especially important for the establishment of a permanent human presence on the moon, as such an endeavor has not yet been attempted. The issue with sending massive rovers, however, is that one rover cannot study everything. Oftentimes, the physical area one rover can cover is limited in both distance and scope, sometimes difficult to traverse due to rough terrain. Additionally, there may be a limitation on the types of data the rover can collect because of volume and weight restrictions.

Because of these issues, the best solution is to introduce CubeSat rovers. CubeSat rovers are a novel combination of a CubeSat bus and all its functionality, as well as the mobility of a conventional rover. A CubeSat can be made modular and customized to the mission it is being made for, thus allowing it to be developed and launched quickly once a base design has been established. A swarm of CubeSat rovers with a wealth of variations can collect far more data cost-effectively compared to a singular rover with higher chances of failure and longer development time. The future of efficient, affordable and data rich planetary exploration missions lies with CubeSat rovers and the opportunities using them will provide.

1.2 Literature Review

1.2.1 Planetary Rovers Background

1.2.1.1 Historical Timeline of Planetary Rovers

The scope of this project is limited to the lunar surface, however, there is a rich history of planetary rovers to pull from when considering historical data. One of the first rovers sent to study the moon was the Russian rover *Lunokhod 1* in 1973 [3]. This first rover was remote controlled and had a built-in heating system and motion control. Instruments were protected by a vacuum sealed chassis, and each wheel had its own motor for movement.

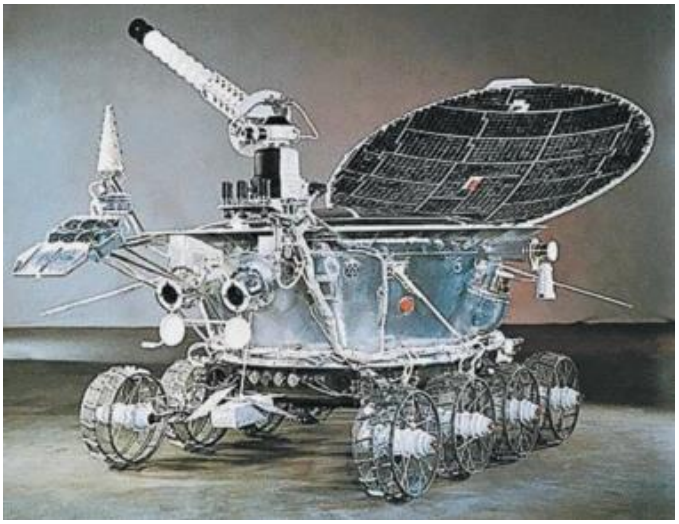

Figure 1.1 Lunokhod 1 [3]

Following the launch of the Apollo program, the first American rovers on the moon were roaming vehicles used by astronauts to traverse the lunar surface [4]. Fast forward to Mars exploration missions, the first rover sent there was *Sojourner*, which operated in 1997 [2]. *Sojourner* was unique in that it used commercial off the shelf components (COTS) for the motors on each wheel, which kept costs down [5]. This is an important precedent for future development of CubeSat rovers, as this will aid in both efficiency and low-cost alternatives to full-fledged planetary rovers.

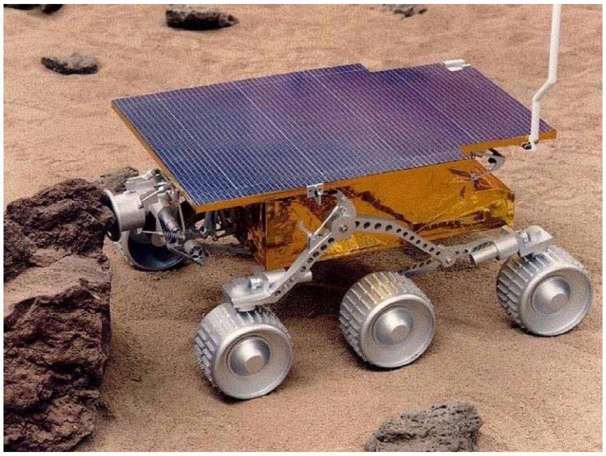

Figure 1.2 - *Sojourner* in a test environment [2]

As exploration of Mars continued, other rovers joined the ranks such as *Opportunity*, *Perseverance* and *Curiosity*. Notably, Opportunity collected spectroscopic data of the Martian surface that is useful for understanding the soil and environment's composition. This will be elaborated on in further detail in section 1.2.3.

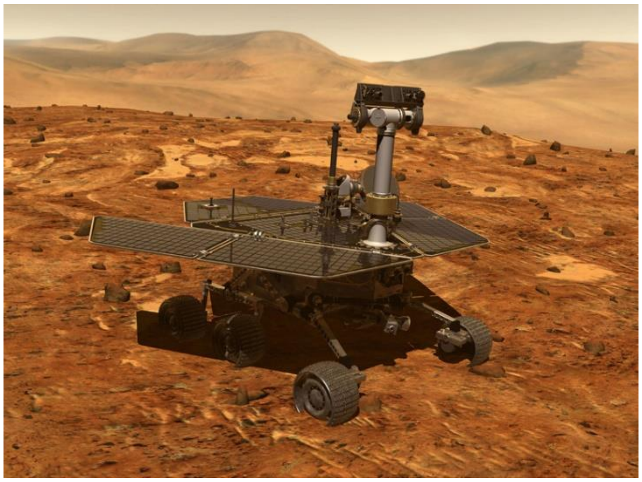

Figure 1.3 - Illustration of the *Opportunity* rover on Mars [6]

1.2.1.2 Lunar Missions of Interest

Most recently, there are more efforts to study the lunar surface with rovers as well. China sent the *Yutu* rover to the moon in 2013 and has been collecting data from 2013 to 2016 [7]. A second mission from China, *Yutu 2*, is currently the only active lunar rover on the moon as of 2022. Future missions planned for the moon include most notably, *Colmena* [8], *Asagumo* [9], *MoonRanger* [10] and *Smart Lander for Investigating Moon (SLIM)* [11]. These missions are of interest to the scope of this project, because they encompass one or more traits of the proposed CubeSat rover mission: small size, focus on modularity, or spectrometry and atmospheric research.

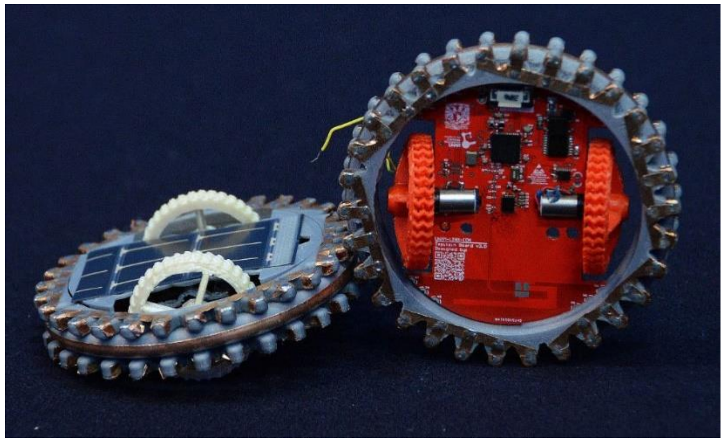

Figure 1.4 - One of the *Colmena* rovers [8]

Colmena is particularly interesting since the success of the mission will define the possibilities of deploying a swarm of micro rovers in future missions. This is in line with the idea behind CubeSat rovers as well, since the idea is that each rover would have its own specialized sensors and scope for planetary exploration. For rovers such as *SLIM*, the technology of interest is its landing and mobility system. The rover is set to land and deploy inflatable wheels to move around the lunar surface, which is important to consider for other small spacecraft that are similar in size [12]. Precision landing will be a challenge for smaller rovers, and the success of the *SLIM* mission is going to serve as an important technology demonstration for landing.

Another project of interest is the *AMARIS* CubeSat rover, specifically because it is designed to be deployed on the moon, and it is also a rover like the proposed project [13]. This project focuses on dust accumulation on solar panels for rovers on the lunar surface, which is not a design concern for the scope of the CubeSat rover project. The structure, scope, and the deployment of *AMARIS*, however, is still helpful for the development of future CubeSat rovers.

1.2.2 CubeSats Overview

CubeSats were first introduced in the early 2000s, after collaboration between Stanford University and California Polytechnic State University [14]. Professors Jordy Puig-Suari and Bob Twiggs proposed a reference design for CubeSats, which later went on to become the standard for the satellite, and the first CubeSats were launched in 2003 [14]. A standard CubeSat is measured in units, one unit being defined as 10 cm x 10 cm x 10 cm in volume. The idea behind using CubeSats was originally for educational purposes, however they have become ubiquitous for space research and exploration [15]. The low-cost, faster development and modularity of CubeSats have made them a popular alternative to bulky, traditional satellites. They are especially useful for educational use, as well as for rapid research and development, since many CubeSats use COTS components when built.

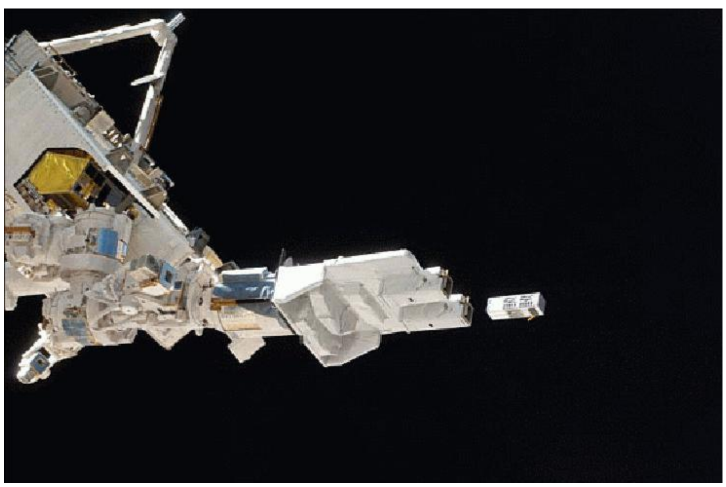

Figure 1.5 - *TechEdSat-1* being deployed from the ISS [16]

A distinct advantage CubeSats carry is that once a heritage CubeSat design is established, it can be modified and modularized to fit the latest mission requirements. These satellites range anywhere from 2 to 12 units in size and can be launched in swarms or as singular satellites based on the scope of the mission. Some CubeSat missions of interest for this project include *PhoneSat* and *TechEdSat* from NASA Ames Research Center, and *MarCO* from the Jet Propulsion

Laboratory [17]. For the scope of the proposed project, *TechEdSat* is an important heritage satellite to consider because of the success of past missions, accessibility, and modular design that is adapted to each subsequent mission. The scope of *TechEdSat*, especially *TES-6,* is to focus on the entry, descent, and landing applications of CubeSats for future planetary missions [18]. This is in line with the intent of CubeSat rovers, which would land on the surface of the moon or Mars for planetary research.

1.2.3 Spectrometry and Applications in Space

In previous missions to Mars, spectrometry data has been used to study the composition of the Martian surface via rovers such as *Opportunity* [19]. There are several methods of collecting spectroscopic data: infrared spectrometry is used to check the composition of the atmosphere, and hyperspectral imagery is used to look at the composition of various materials, such as mineral composition in soil. Spectroscopy is an incredibly useful tool to study the composition of solid materials such as rocks and soil to get data on their composition. Data from the *Opportunity* mission was compared with similar data from earth, and the quality and composition of the Martian soil was shown to be iron rich and in some cases like sulfate rich soil depending on the sample [19]. The success of these readings is an important steppingstone for data collection on the moon and further study of Mars.

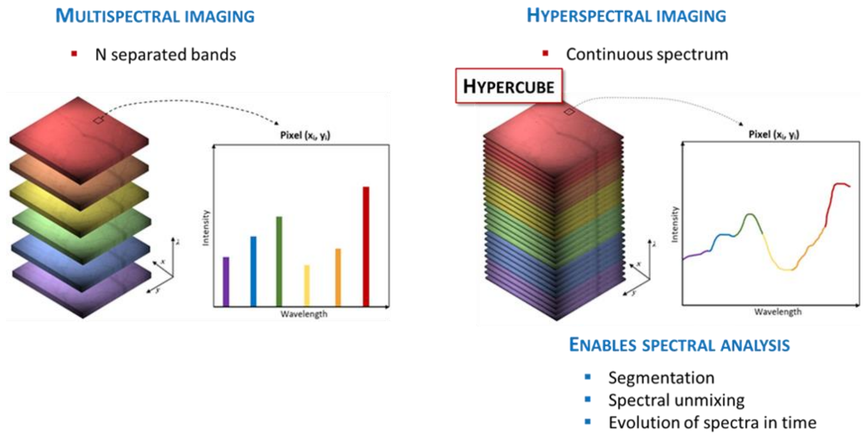

Figure 1.6 - A diagram illustrating how hyperspectral imagery works [20]

For the scope of this project, the spectroscopy data collected will help determine the composition of lunar regolith. The best choice for the spectroscopy data that needs to be collected is the hyperspectral imager. Mineralogical studies on the moon via *Chang'E* with hyperspectral imagery has already been shown to be comprehensive and useful in obtaining a snapshot of the lunar surface [21]. Utilizing a smaller size imager for up close study of the lunar regolith can provide useful data on building materials based on the composition.

Once a base is established on the moon, it will become difficult to transport fresh building materials and resources from earth. This emphasizes the need to use whatever is available on the moon already, so understanding the composition of various minerals and materials is paramount to sustainable development. There are also applications in atmospheric sensing, such as sensors used to study pollutants in earth's atmosphere [22]. These can be adapted to study the lunar atmosphere for gases that can potentially prove harmful to astronauts, or useful as a resource if needed.

1.2.4 Atmospheric Sensing

While the lunar surface does not have a thick atmosphere, there is still a detectable amount of material and gas present. Additionally, there is the ever-present risk of radiation on the moon that must be considered before establishing a crewed base, so atmospheric sensing is necessary before any measures to develop a base can be taken. During the *Apollo 17* mission, atmospheric data collected on the moon found noticeable amounts of hydrogen, helium, ammonia and even trace amounts of carbon dioxide and water in the lunar atmosphere [23]. Further analysis will be crucial to evaluating whether these materials can be extracted from the atmosphere, or if they will pose a hazard to crews living on the moon.

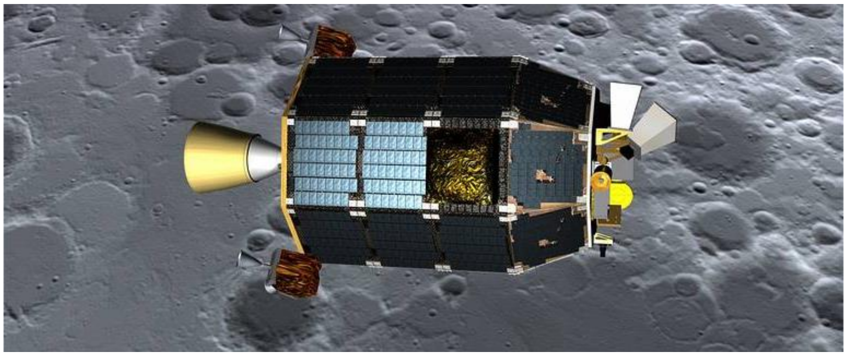

Figure 1.7 - Illustration of LADEE hovering over the lunar surface [24]

More recently, the *LADEE* mission from NASA Ames found that the moon's atmosphere is quite complex. Readings from the mission found several elements to be prominent in the lunar atmosphere, and data collected placed the moon's atmosphere in the surface bounded exospheres category [23]. Exospheres are the outermost section of a planet's atmosphere touching space, with a denser atmosphere below it. Study of the Moon reveals that it only has an exosphere bound to the surface, and no substantial or dense atmosphere below this layer. Other planetary bodies that share a similar atmosphere include Mercury, which also has a surface bounded exosphere [25]. It is important to study the atmosphere for astronaut safety, and the readings can be exceptionally important to understanding the variations in atmosphere for other planets in the solar system and beyond as well. For the scope of this project, however, to study the lunar atmosphere, an array of sensors will be necessary to get an accurate picture of what is present on the moon. Radiation, gas, and general atmospheric sensors will be utilized to take these measurements.

1.3 Project Objective

For this project, the objective is to design and develop a CubeSat rover capable of basic spectrometry and atmospheric sensing of the lunar surface. The rover's objective is to get a clearer snapshot of the lunar surface, for a better understanding of both the lunar atmosphere and the composition of the lunar regolith. This data will be invaluable in establishing a permanent lunar base fit for human habitation. Due to the small size of the project, affordability and efficiency with resources and space will be crucial. The most pressing design challenge will be optimizing sensors and tools into the volume of a standard 6-12U CubeSat

1.4 Methodology

The proposed methodology for this project includes studying available documentation for previous satellites such as *TechEdSat*, spectrometers used in space applications, and rover designs to produce the basic structure of the CubeSat rover. Basic requirements will be adapted to the mission scope, including structural, mechanical, electrical and controls requirements. To conduct a proper assessment of the lunar surface, the CubeSat rover must include a braking system, mobility, atmospheric sensors, and a spectrometry tool suited for the mission. The assumption is that these rovers will be deployed from lunar orbit from a larger spacecraft housing additional rovers in the swarm. The rover will use COTS components and borrow basic structure from existing projects. Ideally, the timeline for such a project would be completed in 12-18 months, given the smaller size of the rover, and that development of other specialized rovers can be done in parallel if needed.

This project will serve as a top-level design study for a potential rover swarm mission to the Moon, so after researching the possible subsystems and components, recommendations to move forward on the design will be provided.

Chapter 2

Background

This chapter outlines some background and previous missions and projects this project will be based on. Components such as structure, payloads, or general mission design will be inspired by or borrowed from predecessors. Furthermore, this chapter will cover any new developments in missions to the Moon pertaining to the Artemis program.

2.1 Previous Missions

Much of the inspiration for the CubeSat rover comes from previous lunar missions. The following table covers a brief overview of several lunar missions of interest, along with important instruments, power systems and mass properties.

Table 2.1 - Early lunar missions of interest

<table>
<tr><th colspan="6">Early Lunar Missions of Interest</th></tr>
<tr><th>Spacecraft</th><th>Size</th><th>Weight</th><th>Power</th><th>Key Instruments and Notes</th><th></th></tr>
<tr><td rowspan="5">Ranger</td><td rowspan="5">10’3”x15”

312.42x 457.2cm</td><td rowspan="5">784.2 lb

355.7 kg</td><td rowspan="5">Solar panels, AgZn battery with 1000 W-hours, AgCd battery operational for 30 days</td><td>Vidicon television camera, gamma-ray, spectrometer, seismometer, telemetry including 960 MHz transmitters</td><td rowspan="5">Notes
[26] [27]</td></tr>
<tr><td>Category</td></tr>
<tr><td>Orbiter</td></tr>
<tr><td>Year</td></tr>
<tr><td>1961-1965</td></tr>
<tr><td>Purpose/ Impact</td><td colspan="5">Transmit lunar surface images to Earth stations, and collect various sensor data including spectrometer data, allowing for a comprehensive look closer to the Moon’s surface. The creation of the Deep Space Network for tracking of the Ranger missions gave an unprecedented view of the dimensions and composition of the Moon.</td></tr>
</table>

Surveyor	3.3 m high 4.5m diameter	995 kg (at launch) 292 kg (at landing)	Solar panel with 85 W output, main and additional battery had combined output of 4090 W	Star-37 retro motor for braking, cameras, strain gauges, magnets on footpads, temperature sensors and alpha-scattering instrument for surface measurements **Category** Lander **Year** 1996-1968	**Notes** [28]
Purpose/ Impact	Validate and develop soft landing technology, with emphasis on providing data on the compatibility of the Apollo spacecraft design. Additionally, the Surveyor program aimed to gain more data on the conditions present on the lunar surface; this added to understanding of the Moon for future missions.				
Prospector	1.37m diameter 1.28m high	296 kg (fueled) 158 kg (dry)	202 W Solar cells mounted on the body, as well as 4.8 amp-hour NiCd battery	Gamma ray spectrometer, neuron spectrometer, magnetometer, electron reflectometer, alpha particle spectrometer, and doppler gravity experiment **Category** Orbiter **Year** 1998-1999	**Notes** [29] [30]
Purpose/ Impact	Designed for a low polar orbit investigation of the Moon. The main purpose was mapping of surface composition and possible polar ice deposits. Other measurements include magnetic fields, and lunar outgassing. This mission was integral to mapping surface composition of the Moon, and improving the understanding of evolution, origin, and any resources on the Moon.				
Luna 24	3.96 m tall with a 50 cm diameter return cabin	5600 kg (fueled) 1880 kg (dry)	Solar powered with a 574 amp-hour battery	Television camera, radiation sensors, temperature monitors, retractable arm for sample collection and sample return capsule **Category**	**Notes** [31]

				Lander **Year** 1976	
Purpose/ Impact	The last spacecraft in the Soviet Luna series, it was the third successful lunar sample return mission in that series. It brought back approximately 170 grams of lunar material for study. This is a predecessor to future, more autonomous sample return missions that can be developed.				
SELENE	2.1m x 2.1m x 2.8m (main body upper section)	2900 kg at takeoff	3.5 kW max power	X-ray spectrometer, gamma ray spectrometer, multiband imager, spectral profiler, terrain camera, lunar radio sounder, laser altimeter, various other atmospheric imagers, and spectrometers **Category** Orbiter **Year** 2007	**Notes** [32]
Purpose/ Impact	A JAXA mission with a focus on studying the Moon's gravity comprehensively along with other atmospheric data. To date, SELENE has helped produce the most detailed map of the Moon's gravity yet acquired.				
Clementine	1.88 m and 1.14 m across	424 kg	Solar panels	Lightweight small imaging sensors and gallium arsenide solar panels. Included 15 novel flight technologies and 9 science experiments onboard **Category** Orbiter **Year** 1994	**Notes** [33]
Purpose/ Impact	Notable for being one of the first lunar missions in over 24 years after the Apollo program, Clementine was launched to test spacecraft components and their performance after prolonged exposure to space. Additionally, mission objectives				

[redacted]	included studying the Moon and a nearby asteroid. With Clementine, a comprehensive look at lunar features such as the poles was given. Evidence of ice in permanently shadowed craters was also discovered.

The spacecraft selected for the table were chosen specifically for their size and the importance of the scientific data collected with each mission. Some of these parameters may seem familiar later as various aspects of the CubeSat rover design are discussed. The rest of this section will cover other missions of interest, and the characteristics of each that will be important to establishing the design of the CubeSat rover.

2.1.1 CAPSTONE Mission

While several lunar missions have been attempted throughout history, there are few CubeSat missions of interest. For the Artemis program, the first definitive mission is *CAPSTONE*, which will act as a pathfinder for NASA’s planned lunar Gateway mission [6]. The CubeSat itself is the size of a small microwave oven, and weighs about 55 pounds. Some notable aspects of the mission include testing novel maneuvers and figuring out an efficient flight path for future lunar missions.

While the design of the CubeSat is important, what is of importance for studying *CAPSTONE* is the flight path. The mission will involve the CubeSat executing an orbit called a near rectilinear halo orbit (NRHO), which heavily involves gravity to assist the CubeSat to its target orbit [34]. This allows the CubeSat to retain precious fuel, even though the transit time to the Moon will be longer. Using the Sun’s gravity as a flight assist, *CAPSTONE* will take a path far from the Earth-Moon system, and then round back to the Moon with several maneuver corrections along the way. In terms of applications to the proposed project, *CAPSTONE* serves as the perfect example of fuel efficiency and establishing a novel orbit around the Moon, which can serve useful for finding a landing site and areas of interest to study.

Figure 2.1 - Artistic rendition of CAPSTONE in orbit around the moon [6]

On a design basis, without the need for a rideshare launch vehicle or substantial amounts of fuel, the volume and budget of the CubeSat rover can be utilized for other important payloads and systems. Furthermore, depending on how well the onboard flight computers work on *CAPSTONE*, the basis of the design can be used as inspiration for a similarly sized satellite. While there were some difficulties in establishing a communication link between *CAPSTONE* and the Earth, those issues have been resolved and the satellite is back in contact with the ground station [35]. Special consideration will have to be given to establishing a reliable software subsystem for the CubeSat rover, as satellites and spacecraft commonly lose contact with Earth on their way to the Moon.

2.1.2 Lunar Flashlight

A JPL mission, the *Lunar Flashlight* is set to be launched in the future along with other Artemis related Moon missions. Measuring the size of a briefcase, the *Lunar Flashlight* is designed to study the lunar ice caps via spectrometry and onboard lasers, the first of its kind [36]. This is especially interesting for the proposed CubeSat rover project, as the findings from the spectrometry data will be informative as to the effectiveness and accuracy of these tools for studying the lunar surface. The CubeSat rover will have an onboard spectrometer that will be outfitted to study the lunar regolith and look for composition that may be useful for building materials or show signs of water. If the *Lunar Flashlight* mission is successful, this data will be immensely useful in developing the spectrometry payload on the CubeSat rover project. Since the mission is still in development, further details are not known, but the greenlight on the Lunar Flashlight mission is reason enough to explore the applications of spectrometry on the lunar surface.

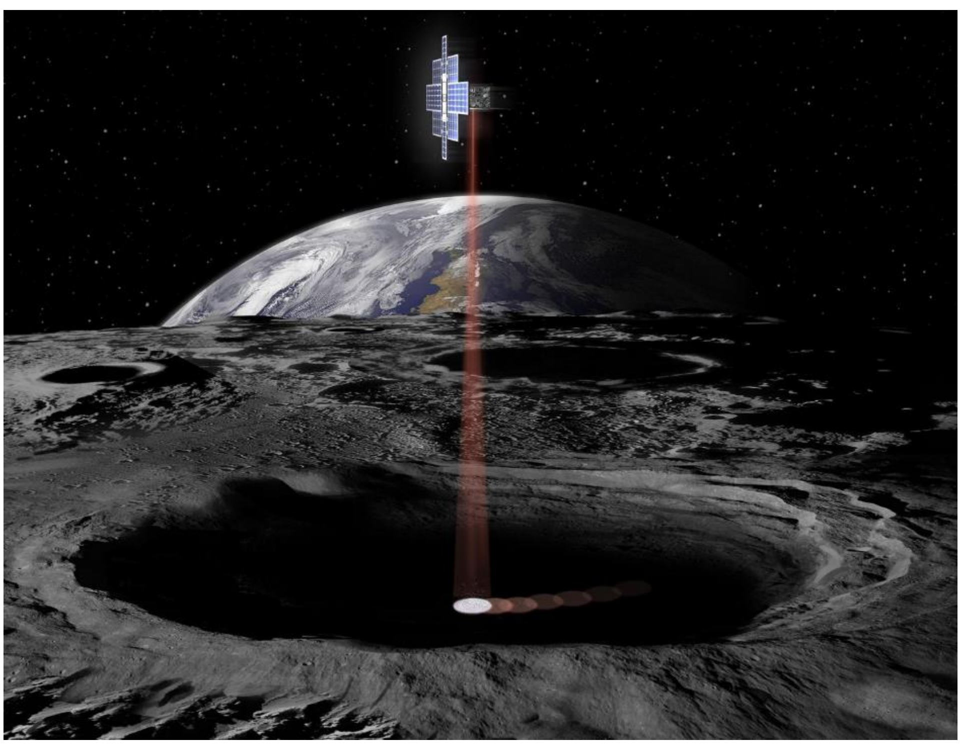

Figure 2.2 - Artist's rendition of the Lunar Flashlight [37]

2.1.3 TechEdSat

With several successfully completed missions, *TechEdSat* is an important predecessor in CubeSat projects that can be used as a basis for some of the CubeSat rover's structure. *TechEdSat* is notable for several reasons, for its key technological advances; Of interest are the ISS compatible design and communications systems [38]. To avoid exorbitant costs for a rideshare mission, it is simpler to launch a CubeSat from the ISS directly. Following the same safety features as *TechEdSat* ensures a safe launch for both the CubeSat and the astronauts aboard the ISS. Additionally, communications are often where many Moon landers fail. *TechEdSat*'s communication system operates by connection to a network of satellites via the Iridium module.

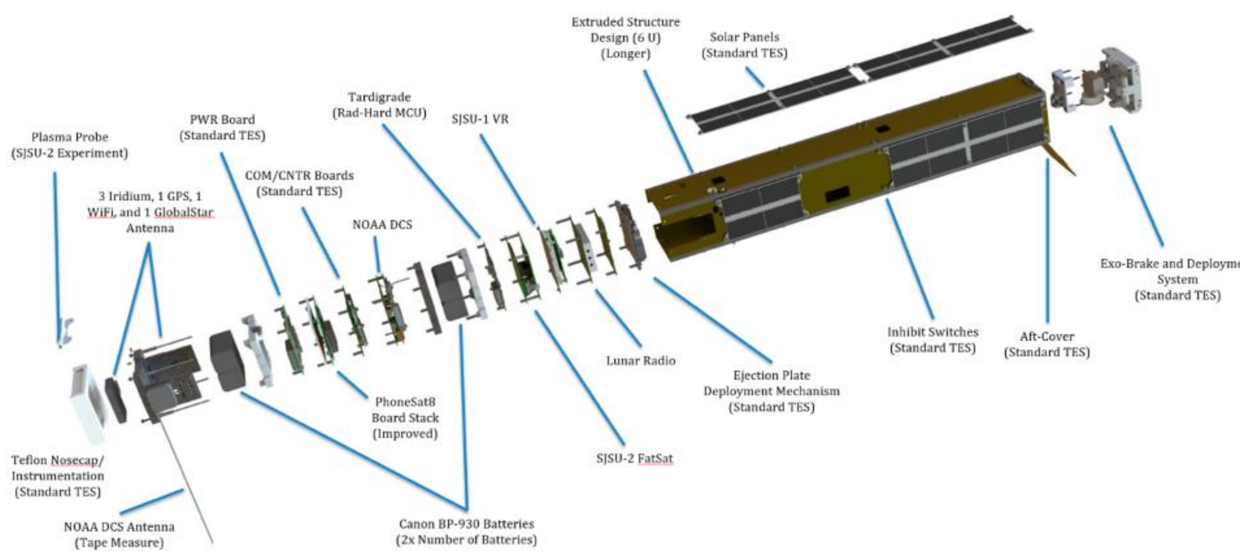

Figure 2.3 - Isometric view of *TechEdSat-8* [16]

Pictured in Figure 2.3, the isometric view of *TechEdSat-8* shows a typical composition of the satellites, with much of the payloads being the same such as the Exo-Brake, Iridium module, and various other sensors. For the sake of simplicity and leveraging previous work done, the

CubeSat rover will utilize much of the same communications and onboard computer systems to function in the software subsystem. Because of *TechEdSat's* modular design, it is easy to take the basic structure and swap out payloads depending on the size and requirements of the CubeSat and related mission.

As mentioned in section 2.1.1, there is going to be an emphasis on proper communication channels for data collection and general comms operations for the CubeSat rover mission to be successful. Establishing a link via a satellite network with downlink capability will be essential to achieving this. Without it, there is little reliability that the data harnessed from studying the Moon will be transmitted back to Earth for study. Since there are no concrete plans for retrieval of the rover, data collection is a high priority for nominal mission success criteria. Specifics on the software and communications subsystems will be elaborated on in Chapter 3.

2.1.4 Lunar Sample Return Mission

Shortly after Apollo 12, a successful lunar sample return mission was conducted by the then Soviet Union. A total of three locations were sampled, and samples were returned via robotic sampling missions [39]. What may be important with this mission is the lander itself, which consisted of a descent portion and equipment for ascent and recovery. While there is no pressing need for recovery, there is the issue of damage when landing the CubeSat rover. Because the Moon lacks a proper atmosphere, there is difficulty in trying to land equipment and spacecraft on the surface. It is not unheard of to see lunar landers and rovers losing contact and crashing into the lunar surface. It is important to establish a landing site, proper landing gear and make sure the payload is unharmed. Looking at the *Luna 24* structure, it is pertinent to include the descent stage of the vehicle in the overall design of the CubeSat rover.

Figure 2.4 - Rendering of the *Luna 24* lander [40]

While the lander itself is bulky and weighs close to 1800 kilograms without fuel, this weight can be reduced and optimized with newer, lighter materials. There will be an ascent portion of this vehicle, as the CubeSat rover is meant to stay on the lunar surface to collect data for only a limited duration. Having a descent stage attached to the CubeSat rover while landing would guarantee the payload is intact, while also being a source of fuel for maneuvers while in orbit and when landing. For the sake of simplicity, this descent stage will detach from the CubeSat rover itself and will not be designed in detail.

2.1.5 Apollo Lunar Surface Experiments Package

Introduced with the Apollo missions, the Apollo Lunar Surface Experiments Package (ALSEP), is a package of several data collection tools and experimental instruments to learn more about the Moon. While many of the tools used in ALSEP are dated, there were plans for the Apollo missions that included new experiments such as mass spectrometry and the inclusion of an optical and radar observatory [41]. While much of the data has since been lost or difficult to access, instead the experiments conducted with ALSEP will be adapted to the new swarm of CubeSat rovers. The idea behind making a CubeSat rover is to split up the experiments and data collected about the Moon and the lunar surface and spread it out amongst several micro-rovers that will be deployed in swarms. For this project's sake, only spectrometry experiments will be conducted on the CubeSat rover being developed.

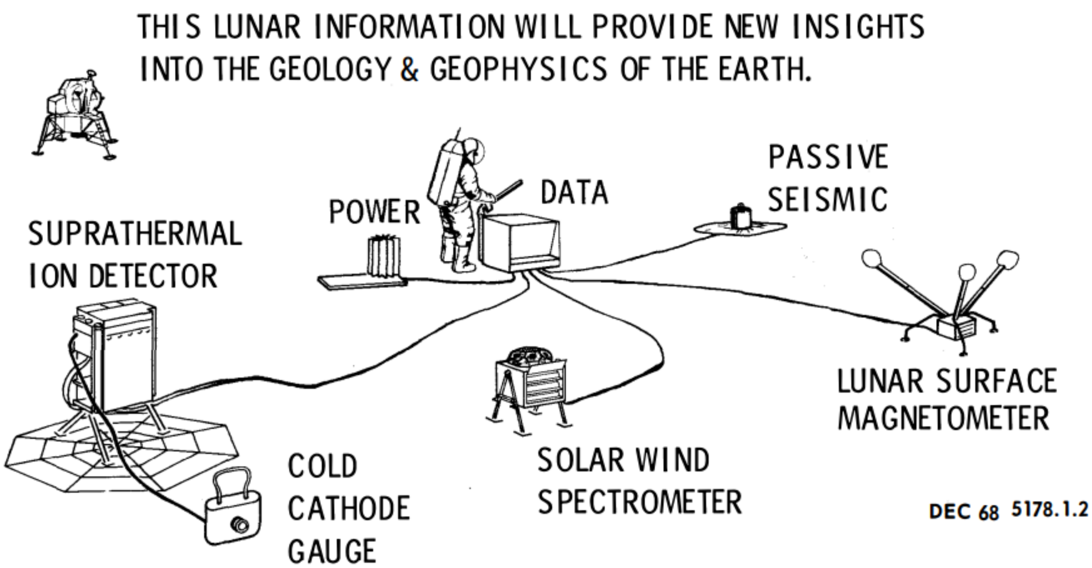

Figure 2.5 - Experiments in ALSEP from an ALSEP handout [41]

2.1.6 Diviner Study of Lunar Temperatures

While studying data from the NASA Lunar Reconnaissance Orbiter, researchers from University of California Los Angeles (UCLA) were able to determine areas of the lunar surface with habitable temperatures via Diviner data and thermal modeling [42]. Findings from the mission highlighted that there are pits on the surface of the Moon with stable temperatures of about 63 degrees Fahrenheit, making these areas habitable and comfortable for humans. The pits were first discovered in 2009, and further studies done by the UCLA team found that of the 200 or so pits, 16 may be collapsed lava tubes, explaining the present temperature.

A major instrument involved in the study of the Moon is Diviner, a nine-channel radiometer used to take measurements of the temperature [43]. For the sake of simplicity, much of the data modeled was limited to the pit floors, as adding the walls would increase the complexity and difficulty of thermal modeling. In addition to the data collected by Diviner, thermal models were also made and studied of the Moon's temperatures in different areas. A 3D thermal model made by researchers is shared in Figure 2.6:

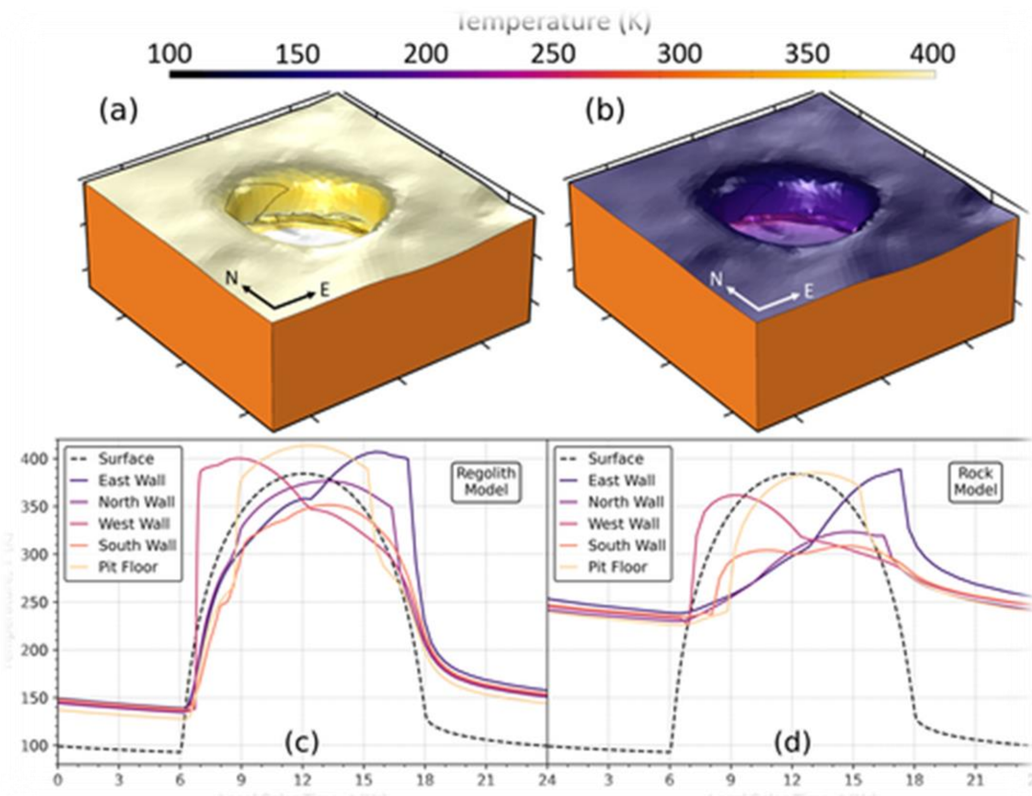

Figure 2.6 - 3D thermal model of a lunar pit made by UCLA researchers [43]

The most important takeaway from the research is that thermal pits have an insulation effect on the temperature as the Moon shifts from day to night. Because of their shape, they become effective heat traps, allowing the pits to stay warm even when temperatures shift to 280 degrees Fahrenheit below zero at night. This shape also shields the pit floors from excess radiation, temperature changes and impacts from debris compared to the rest of the lunar surface, making them an ideal area for the study of habitation locations. If further rovers or probes can be sent to pits marked as areas of interest, a more detailed picture of the pit environment can be established.

While this mission is not linked to the mechanical aspect of the CubeSat rover mission, it provides excellent context for the lunar surface environment. Since the goal of building a habitable base is part of the project objective, learning where to best land and study the lunar surface is invaluable. Any additional research that can be done on the temperature, composition, and topography of these lunar pits, should be a priority when considering the establishment of a lunar base. The exploration of these lunar pits will be the crux of the CubeSat rover recon mission.

2.1.7 Historical Data on Rover Power Systems

To effectively study the Moon in both day and night cycles, it is necessary to have two separate rover designs for each integrated into one for full day functionality. One aspect of rover power systems is the use of radioisotopes in tandem with solar panels and batteries. Historically, nuclear power has been used with solar or batteries, if not exclusively. The historical power systems will be elaborated on in Chapter 5.

2.2 Design Methodology

2.2.1 Overview

To achieve a shorter mission timeline, ideally 18-20 months, previous missions and COTS components must be leveraged for the design of the CubeSat rover. This will significantly reduce development time and will make overall assembly and analysis much easier. Much of the payload support such as power boards, batteries, and communications tools will be commercially acquired. For the scope of this project, focus will be on establishing a top-level design outline for how the rover may look in terms of what experiments are on it, what kind of power system it might use, the mission scope and other instruments onboard. Sensors would ideally be acquired readymade, and a spectrometry payload will not be designed in detail for the sake of time. A comprehensive subsystem breakdown will be discussed in Chapter 3.

Chapter 3

System Requirements

This chapter will cover the basic subsystems and structure of the CubeSat rover. An overview will be provided for each subsystem, and hardware selection. For the sake of clarity, the mission objectives will be laid out for the project to clarify what part of the mission this rover will satisfy.

3.1 Mission Overview

As mentioned in previous chapters, the CubeSat rover will be one in a swarm of rovers that will study the lunar surface. If following the Artemis mission timeline, it is assumed that the lunar gateway will be deployed and fully functional. This will allow the CubeSat swarm to communicate with one centralized body and organize the data collection. Each CubeSat rover will be deployed with different payloads assisting in the Moon analysis. A mission concept of operations (ConOps) is outlined below:

Mission Concept of Operations

1. **Pre-Launch:** Verify that the CubeSat rover meets basic functional requirements and passes all necessary testing
2. **Launch:** CubeSat rover is launched unpowered and sealed until it reaches lunar gateway
3. **Deployment:** Rover is powered on, deployed to lunar surface, and establishes a connection with the lunar gateway in transit
4. **Landing:** Once landed on the moon, wheels and experimental payloads will deploy
5. **Experiment Duration:** Mission duration will be 3-6 months; this project will test spectrometry and atmospheric sensing experiments and collect data on lunar pits
6. **End of Life:** CubeSat rover will return to lander it was deployed on and be sent back to Earth for processing

This rover will focus on only spectrometry and an atmospheric sensing package payload. For the scope of this project, the wheels and basic rover design sans payloads will be explored further for analysis and design as well.

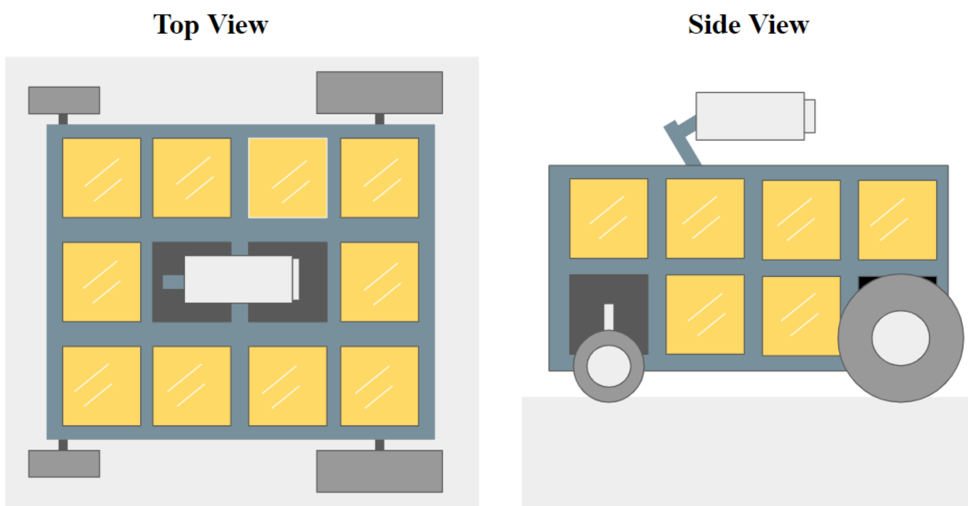

Figure 3.1 - Preliminary mockup of the CubeSat rover with spectrometer

3.1.1 Mission Design Overview

Some important considerations for the mission operations overall will be the landing site and what kinds of designs for the landing gear may be necessary for the rover to be successfully deployed. Part of these constraints include the topology of the lunar surface and pits that will be studied, as well as calculations for the force of impact if the rover is airdropped into a lunar pit from the surface.

3.1.2 Concept of Operations (ConOps) Visual

The ConOps of the mission is outlined in the graphic below:

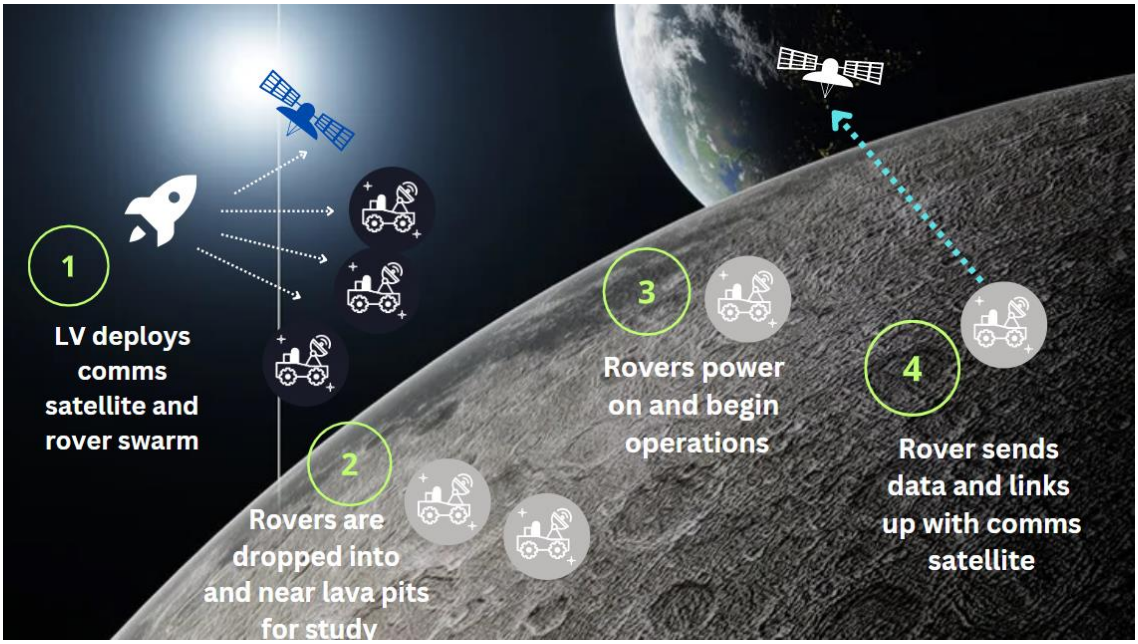

Figure 3.2 – ConOps of rover mission

3.2 Design Constraints

For the CubeSat rover's design, there will be references to NASA workmanship standards and design specifications for CubeSats. As mentioned in Chapter 2, many of the design components will be borrowed and adapted from previous missions that deal with a similar scope. Much of the orbital and debris related constraints for the rover will follow the NASA Goddard Mission Success Handbook for CubeSat Missions (GSFC-HDBK-8007) [44]. Additionally, while the lunar gateway may be fundamentally different from the ISS in some respects, the safety standards are not likely to deviate from those in place for the ISS. For this reason, there will be requirements and safety references pulled from the NASA SSP 57000 document [45].

3.3 Subsystems Overview

This project will be divided into several major subsystems, with further branches explored within the scope of each subsystem. The following payloads will be broken down as follows:

- Structural (Section 3.3.1.1)
- Mechanical (Section 3.3.1.2)
- Electrical/Power (Section 3.3.1.3)
- Sensors/Experiments (Section 3.3.1.4)
- Onboard Computer (Section 3.3.1.5)
- GNC and Communications (Section 3.3.1.6)

3.3.1 Subsystem Breakdown Tree

A visual for the subsystem breakdown is shown in the figure below:

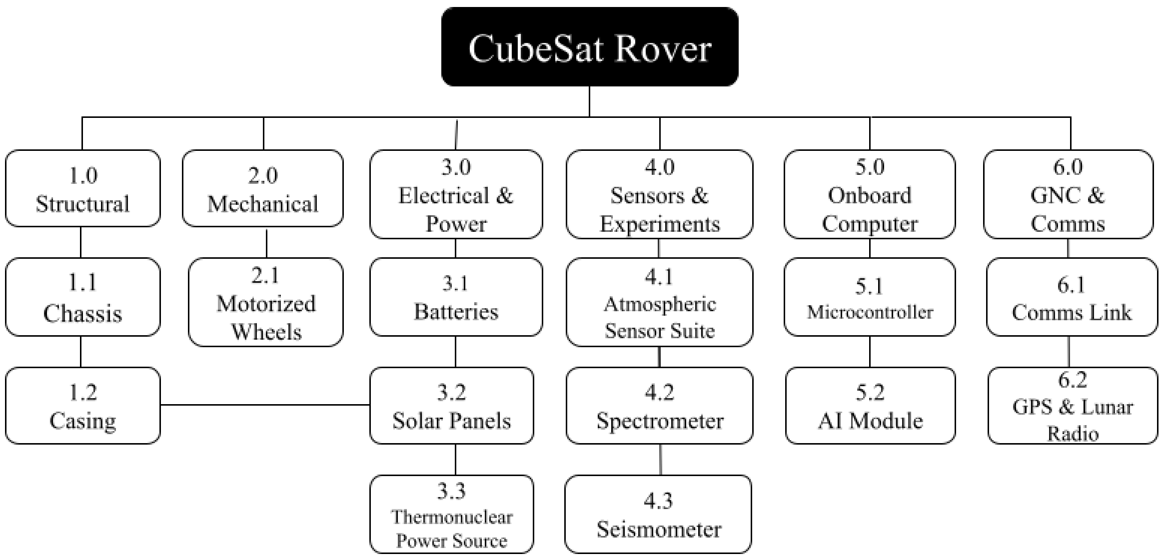

Figure 3.3 – Subsystem breakdown of CubeSat rover

3.3.1.1 Structural Subsystem

The structural subsystem will consist of the chassis and other components of the rover that will house the payloads of the CubeSat. The casing encapsulating the rover and any hardware around it will also be a part of the structure, however, will not be analyzed in depth for this project.

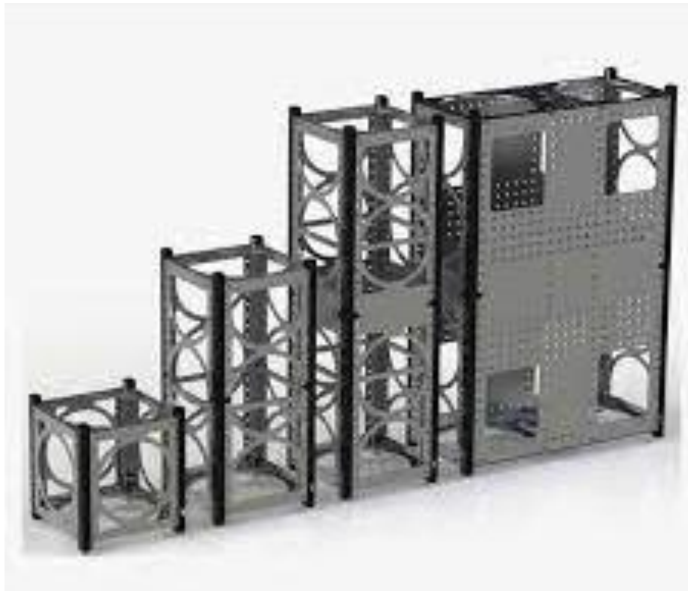

Figure 3.4 – Chassis sizes for a typical CubeSat [46]

As shown in Figure 3.4, this example of a CubeSat chassis from AAC Clyde Space is what is used to make the outer structure of a CubeSat. The frame can be made of whatever materials are necessary for structural integrity, but many frames are made of substances such as aluminum because of how light and strong it is. The number of units are determined by intended volume and mission needs. A stress test on the corners and other stress points will be necessary to determine the best structure for the chassis when designing the rover. Additionally, solar panels can be outfitted on the outside of the frame to aid in power collection while deployed.

3.3.1.2 Mechanical Subsystem

Encompassing the moving or mechanical parts of the project, the mechanical subsystem includes any of the breaking and motorized mechanisms of the rover. A substantial portion of this subsystem is the motorized wheels that will be deployed to handle the rover’s mobility. Significant challenges with this subsystem will be designing the wheels to be compatible with the other payloads in the CubeSat. Making sure the wheels can be deployed easily, while also withstanding the weight of the rover will be part of the design constraints. While the lander may technically also fall under this subsystem, the focus will be on the mechanisms present in the CubeSat body. The wheels would be 3D printed or manufactured with suitable materials for testing the deployment and function but may be made of more robust materials for a flight model.

3.3.1.3 Electrical and Power Subsystem

To fully power the CubeSat rover, great care must be taken in establishing a robust and reliable electrical and power subsystem. Batteries in tandem with an array of solar panels are the likeliest choice as a power source. Design challenges for this subsystem will be making sure the rover can function even with a lack of sunlight, as well as the possibility of extreme temperatures affecting the functionality of the rover itself. The specific sensors and power boards incorporated into the rover will have their own unique electrical requirements. Any power system selected will need to meet the basic criteria, and a rough power budget will be calculated for hypothetical components.

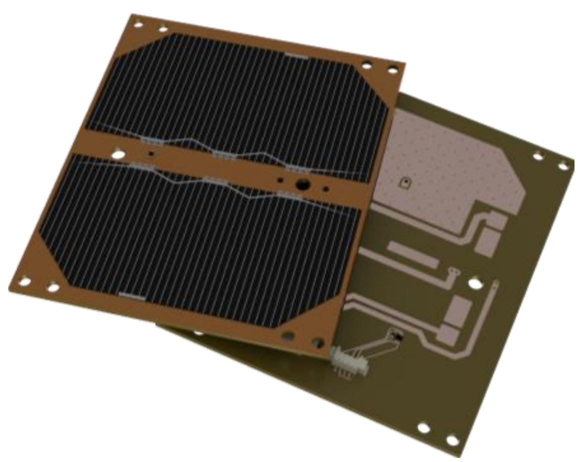

Figure 3.5 – Type of solar panel typically used on CubeSats [47]

For this subsystem, several possible power sources will be explored, as well as compared to the historical data available on small rover and satellite power systems in space. A more comprehensive look at the power subsystem will be elaborated on in Chapter 5.

3.3.1.4 Sensors and Experiments Subsystem

An atmospheric sensor suite and a spectrometer both fall under the sensors category of subsystems. Each with their own unique requirements, both experiments will have their separate branches in terms of breakdown. While at first glance, it might seem inappropriate to include atmospheric sensors onboard, the Moon is known to have a complex exosphere that can be studied in depth to answer questions about what the atmospheric conditions are on the Moon. Radiation measurements can also be included in this section.

3.3.1.4.1 Atmospheric Sensor Suite

For this CubeSat rover, the focus will be on testing and collecting data on radiation, temperature, and pressure. These data will be important for establishing a base on the lunar surface and understanding the nature of the Moon’s complex exosphere. For the sake of simplicity and volume considerations, a multi-sensor with several measurement capabilities will be considered for this subsystem. For rovers that are deployed into lunar pits, they will provide valuable insight and data into the conditions inside the pits. This will help researchers determine the habitability of these formations for future human bases.

3.3.1.4.2 Spectrometer

The most important payload on this project, the spectrometer, must be selected for the efficiency volume wise, as well as range of data that can be collected. The goal of using the spectrometer is to figure out the composition of lunar regolith, and whether the material present is suitable for the use in the construction of a habitable base on the Moon. For this spectrometer, there will be review done on previously used spectrometers in other rover missions, such as those to Mars. Because of the pristine conditions in unexplored lunar pits and lava tubes, there is key data missing as to the accurate composition of the lunar material found inside. Gaining insight into the composition will allow researchers to determine what resources can be collected from the pits in the establishment of a base, or as building material.

3.3.1.5 Onboard Computer Subsystem

Especially important in the overall function of the rover is the onboard computer. This subsystem will consist of several boards that will allow the rover to process and send packages of data to the lunar gateway. Related to this subsystem is the communication subsystem; without an established connection to a gateway, there will be no data transfer or readings to analyze. An AI module is a powerful addition to this subsystem, along with a microcontroller that aids in the computing and controls process in rover operations.

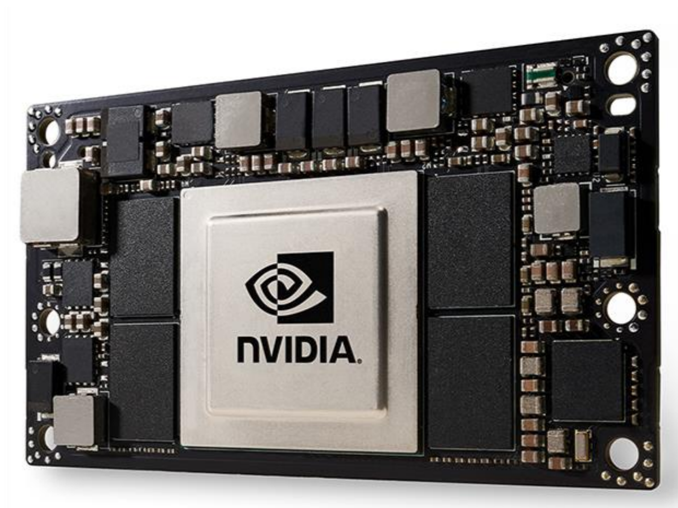

Figure 3.6 – NVIDIA Jetson TX2 module [48]

One selection for the onboard computer is the NVIDIA Jetson TX2, which has AI capabilities embedded into the module. This allows the onboard flight computer to be fast, as well as power efficient. Other options will be explored, but many of the onboard computers will be modeled after *TechEdSat*.

3.3.1.6 Guidance, Navigation, Control, and Communications Subsystem

Without the addition of guidance, navigation and controls systems, the rover will not be able to traverse the lunar surface and collect data as intended. Also, the communications part of the subsystem will allow the rover to establish a link with the Lunar Gateway and transmit data and receive instructions needed to carry out experiments. This may include an onboard radio and antenna. Some constraints to consider include the bandwidth necessary for the link to work, as well as ways to ensure the payload has a backup communications system in case of problems. There is also potential for the rover to tap into the Deep Space Network (DSN) for greater reach, but primary focus will be on establishing a link to the closest reasonable communications system available for a Moon mission.

3.4 Lunar Pit Reconnaissance Mission Operations

3.4.1 Lunar Pits Background Expanded

As covered briefly in Chapter 2, there exist structures on the Moon that have the potential to be excellent locations for lunar bases. Their temperate climate and relative shielding from radiation and debris make them ideal candidates for establishing a functioning base that will be safe and insulated from the otherwise harsh lunar environment. To further expand on the information presented in Chapter 2, the lunar pits in question can be up to 500 feet wide and were first discovered by the Japanese Kaguya orbiter [49]. To date, 200 such pits have been found on the lunar surface and serve as potential drop sites for the CubeSat rover.

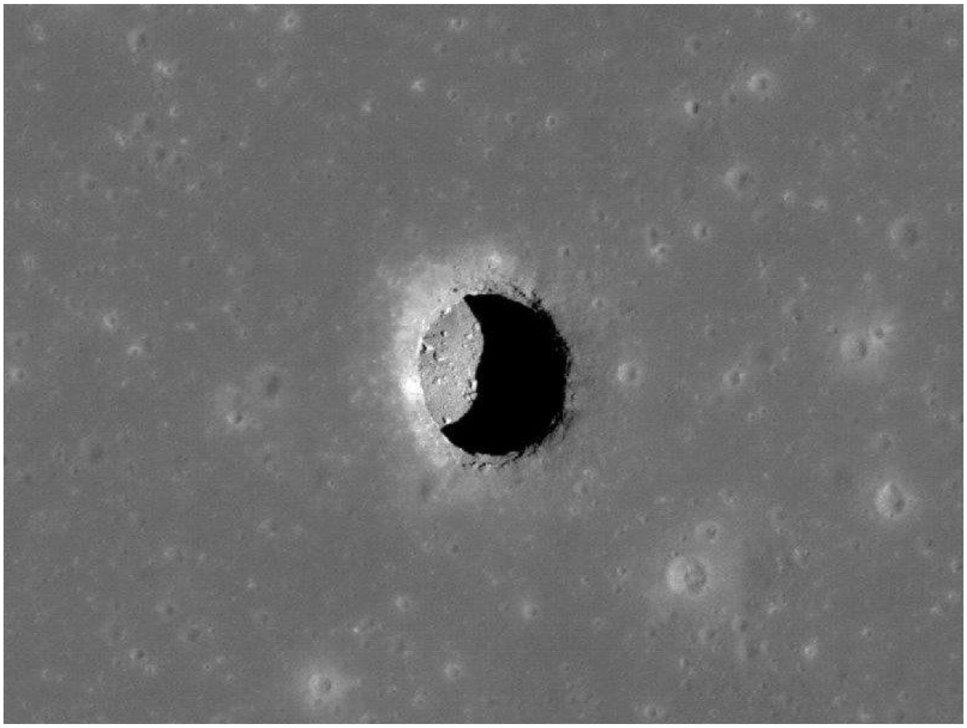

Figure 3.7 – Lunar pit found in the Sea of Tranquility [49]

According to data taken by Kaguya, the lunar pits are most likely empty lava tubes on the Moon's surface [50]. Researchers noted that the lava tubes are shielded from both radiation and meteorite strikes, and because of their pristine condition, would be perfectly suitable for comprehensive study of lunar history. Taking samples and studying the composition of these tubes or pits would be one way of furthering understanding of the Moon's composition, formation and history. This data will also be valuable in determining what resources are available to the first lunar colonists when they need to extract valuable materials for building bases and replenishing supplies.

In 2009, a large pit was found on the surface of the lunar Marius Hills, which seemed to suggest an opening into a lava tube below [50]. This site is just one of many potential drop sites, but for the scope of this exercise, this will be the focus of the lunar drop mission since its dimensions are known to be 50 x 50 meters wide and deep at the opening. Data was collected via radar, and the results are shown in Figure 3.7 below:

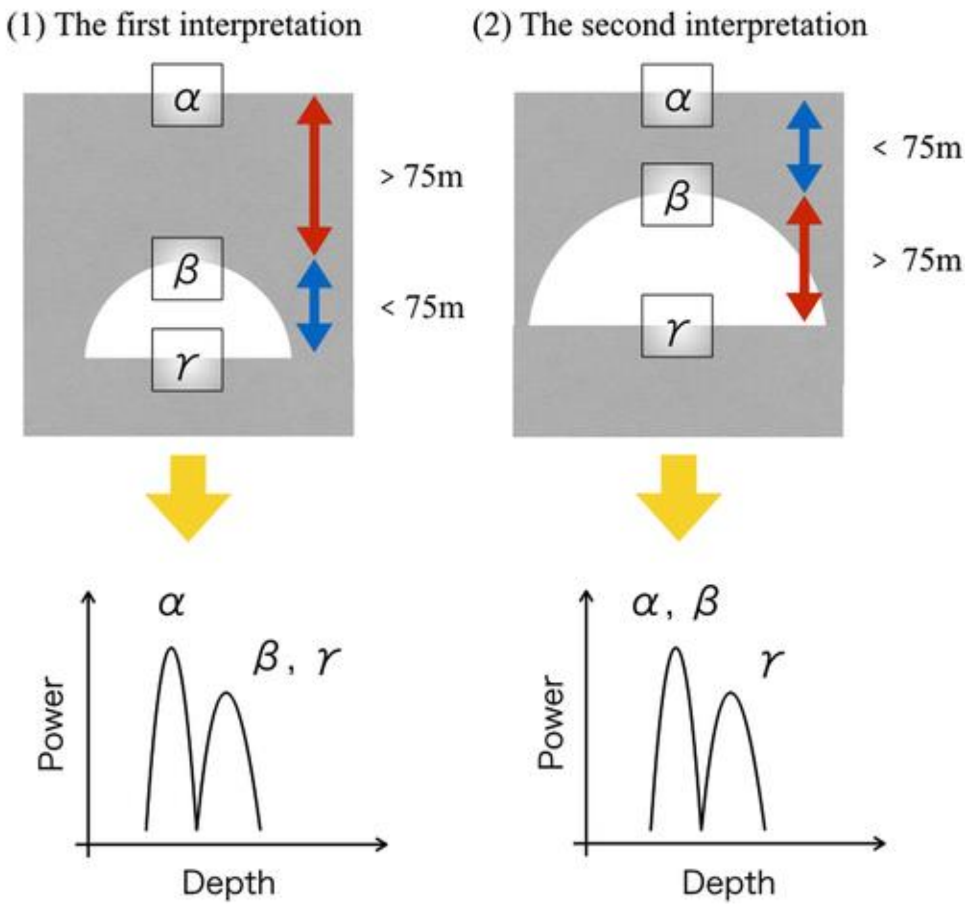

Figure 3.8 - Radar echo data results indicating location and depth of lava tube [50]

There are two different interpretations of the results, but the value that will be important for the scope of this mission is that the total depth may possibly be 75 meters maximum, and thus will serve as the lower limit for drop calculations.

3.4.2 Rover Drop Operations

For the scope of this mission, much of the calculations involved will be regarding the force of impact when the rover is dropped from the highest point on the surface into the lava tubes. As reflected in the ConOps in section 3.1.2, the rover will be dropped from a height above the lunar surface directly into an opening, and the design constraints around the landing gear will mostly revolve around withstanding the force of impact. To calculate force of impact, the following equation must be used:

$$F = \frac{(m \cdot g \cdot h)}{d} \quad (3.1)$$

Where F is the force in Newtons, m is the mass of the object, g is gravity, h is the drop or impact distance, and d is the distance traveled. For simplicity, d will be estimated to be 0.1m. Since the drop will be on the lunar surface, the gravity used for these calculations will be 1.6 m/s^2. To get a varied range of average drop impacts, several calculations will be done with different masses and drop heights. Because of size constraints, the rover mass upper limit will be restricted to 50 kg but will likely remain well below this value. Results are in table 3.1 below:

Table 3.1 Results of drop distance calculations

Spacecraft Mass	Drop Height	Average Impact Force
10 kg	75 m	12,000 N
10 kg	85 m	13,600 N
10 kg	95 m	15,200 N
20 kg	75 m	24,000 N
20 kg	85 m	27,200 N
20 kg	95 m	30,400 N
30 kg	75 m	36,000 N
30 kg	85 m	40,800 N

30 kg	95 m	45,600 N
40 kg	75 m	48,000 N
40 kg	85 m	54,400 N
40 kg	95 m	60,800 N
50 kg	75 m	60,000 N
50 kg	85 m	68,000 N
50 kg	95 m	76,000 N

With these calculations done, whatever the projected mass of the rover will be will determine the type of landing gear used to withstand drop impacts. Rover mass will be explored in further detail in a later chapter.

Further details about instruments included on the rover, as well as the data collected in the mission site will be explored in Chapter 4.

Chapter 4

Instruments and Data Collection

A rundown of the different instruments needed to study the Moon will be outlined in this chapter. Additionally, data collection methods, as well as specific experiments will be expanded on in this section as well.

4.1 Spectrometer

4.1.1 Purpose

To get a good idea of the composition of the Moon's surface, especially in lava tubes or lunar pits of interest, there are some instruments that can be used to collect this data efficiently and accurately. For this mission, a spectrometer will be used to figure out the composition of the lunar materials found in lava tubes where some rovers will be dropped for study.

4.1.2 Possible Hardware

For background on spectrometers used in previous missions, the specific type used by Mars rovers in the past is the Mini-TES [51]. The Mini-TES is an infrared spectrometer, with the capability to determine the minerology of rocks and soil from a distance. While the instrument itself was developed specifically for the Mars rovers, the type of spectrometer is an important consideration in hardware selection, especially for a spectrometer that can be outfitted onto 1 or 2 units of a CubeSat. Mini-TES itself is 2 kg, making it an ideal instrument, size and mass-wise to include on the CubeSat rover.

Figure 4.1 - Mini-TES spectrometer in development [51]

Other spectrometers used for planetary research include the Lunar Ice Cube Mission's BIRCHES spectrometers [52]. Part of a larger mission of a 13 6U CubeSat swarm, BIRCHES is the miniaturized version of the spectrometer on OSIRIS-Rex. While the mission scope for the Lunar Ice Cube Mission involved searching for volatiles on the Moon, the same idea behind the technology can be applied to searching for other types of materials on the lunar surface, such as water or iron.

Based on the overall cost of buying a commercially available spectrometer, it may be more economical to develop a spectrometer in house, in the same vein as other missions to the Moon and Mars. The spectrometer must be able to operate in several environmental conditions, including in darkness or harsh temperatures. Materials of interest the spectrometer must be able to detect include water, iron, other valuable minerals involved in construction, and any organic materials that can potentially be used in farming or agricultural applications. The development of a spectrometer is in and of itself a whole new project to undertake. For the sake of time and simplicity, in an engineering environment, a spectrometer development team would be working in tandem with the rover team to create a suitable payload.

The ideal size and mass requirements match the Mini-TES, ideally no more than 2 kg in mass, and size constraints not exceeding 2U in CubeSat measurements.

4.2 Environmental Data and Experiments

4.2.1 Radiation

While the lava tubes and pits are generally shielded from much of the surface radiation, it is still important to collect the data to ensure a safe habitat for humans to settle in, and whether theories about the formations having less radiation are indeed true. A radiation sensor can be bought commercially as a COTS component, and there are many CubeSat based options that are ideal for hardware selection.

One example is the piDOSE-DCD - Digital CubeSat Dosimeter [53]. The power consumption is 70mW, and it has an operating temperature of –30 to 60 degrees Celsius, making it ideal for use in the lava pits for study. The compact design also makes it an ideal candidate for use in the CubeSat rover, since it was designed for use in CubeSats, and thus has a small size and mass compared to other instruments. This model detects gamma ray radiation, and it has several applications including radiation detection on spacecraft and aircraft.

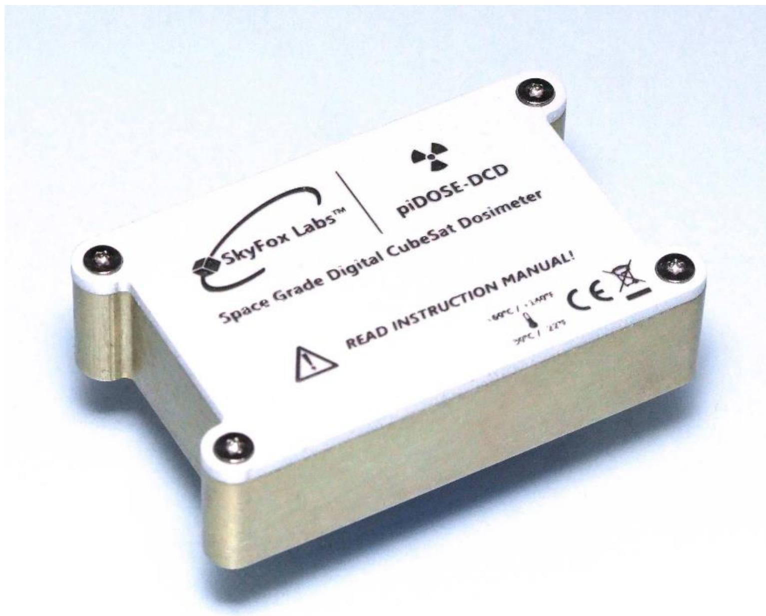

Figure 4.2 - piDOSE radiation sensor [53]

While this is just one example of a suitable radiation detection sensor, other comparable sensors would ideally meet the following criteria: small compact size, low mass, strong detection capability, low power consumption. The only important consideration that may affect use of this sensor is the addition of nuclear power onboard the rover. This may interfere with radiation dosage detection and make data collection difficult.

4.2.2 Temperature, Atmospheric and Pressure Sensors

For the temperature and pressure sensors, this part of the sensor suite is best developed in house, combining smaller components that measure each value onto a bigger unit. Like the Rover Environmental Monitoring Station (REMS) used for the Mars rovers, an in-house developed atmospheric monitoring suite may be the best option for precise monitoring of specific conditions [54].

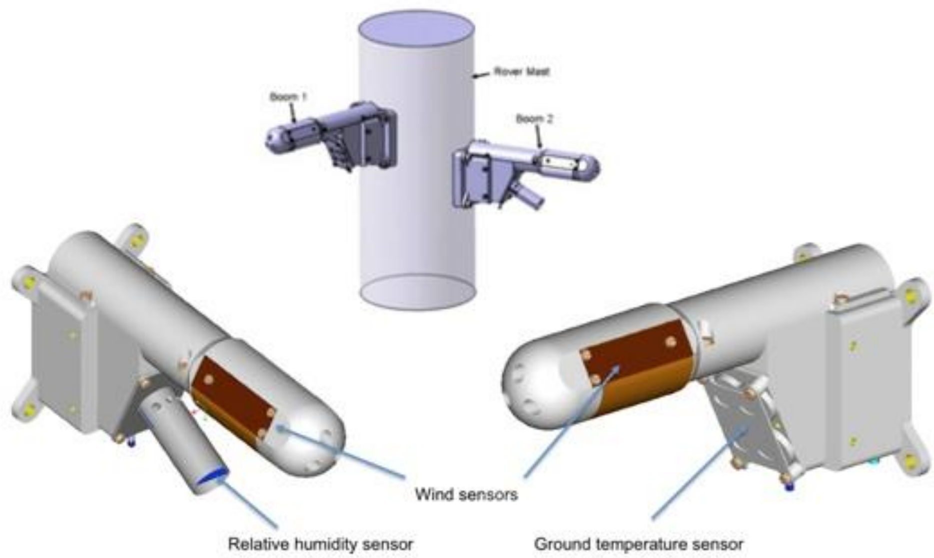

Figure 4.3 - REMS sensor suite for Mars rovers [54]

The sensors that must be included in this suite are temperature, pressure, and ultraviolet radiation. In the absence of other atmospheric conditions, these are the most vital pieces of data that can ideally be collected on the Moon. The temperature and pressure sensors are of utmost importance since they will be confirming the habitable conditions of the lava tubes, and whether the temperature remains approximately 60 degrees Fahrenheit as speculated. The sensors could be designed similarly to REMS, as an apparatus that extends outward once the rover is deployed, or it could be designed in a more compact cube shape suitable for inclusion in a CubeSat form factor.

4.2.2 Recommendations

Based on the form factor of the CubeSat rover, the radiation, temperature, pressure, and atmospheric sensors will ideally take up 3-4U of space on the rover. While there are sensors available for purchase as COTS components, it is easier to take individual smaller sensors and combine them in a form factor that is more realistic for inclusion on CubeSat structures on which the body of the rover is based. This method will reduce the financial burden of buying individualized and more complex sensor suites, instead opting to pick and choose which specific sensors will need to go onto the rover itself.

The next chapter will cover the power subsystem of the rover, and possible options for a power source best suited for the lunar environment.

Chapter 5
Power Subsystem

An overview of the power system and history of power sources for lunar missions will be covered in this chapter. A preliminary power subsystem selection will be made with basic parameters for the design.

5.1 Power Overview

With the advent of smaller spacecraft and robotic missions, there is an increased focus on more efficient, powerful, and compact power systems to power these vehicles. Firstly, here will be an overview of previously used batteries and power systems in small spacecraft of interest. Next, there will be an exploration of power systems that can be used in the CubeSat rover.

5.2 Power Systems Predecessors

In earlier lunar missions, diverse power sources have been utilized. Some of these spacecraft, as referenced in table 2.1, use solar power and batteries to operate. Others use nuclear power instead.

5.2.1 Historically Considered Power Systems

While nuclear energy has been a viable source of power in previous missions, much research has been done to diversify electrical power options for spacecraft. Based on a study into electrical power sources for space applications by the Lewis Research Center, several power sources have been considered as early as the 1960s. Solar cells are among the top choices for electrical power, as they provide adequate power in relatively sunlit areas, while also being flexible and small enough to fit on a variety of spacecraft [55].

Chemical batteries are another viable option, given they are manufactured with the stringent standards required to withstand operating in a vacuum and avoiding dangerous chemical off-gassing. Some features that make chemical batteries a good option is the power output and rechargeability, allowing them to be a good pair with solar cells that can harness energy and store it in batteries for later use. Other power systems considered include fuel cells, Rankine and Brayton cycle systems, and thermionic generators. Of these additional options, the thermionic generators are the least explored, and least likely to be viable with the currently available technology.

As explored in table 5.1 below, nuclear power is also a strong contender for future power systems given its historical use.

Table 5.1 - Nuclear power systems in previous space missions

Spacecraft	Power Source	# Sources	Date	Space Program
Transit-4A	SNAP-3	1	1961	NASA [56]
Nimbus-B-1	SNAP-19	2	1968	NASA [56]
Apollo 12 ALSEP	SNAP-27	1	1969	NASA [56]
Viking 1	SNAP-19	2	1975	NASA [56]
Voyager 1	MHW-RTG	3	1977	NASA [56]
Galileo	GPHS-RTG	2	1989	NASA [56]
Cassini	GPHS-RTG	3	1996	NASA [56]
New Horizons	GPHS-RTG	1	2006	NASA [56]
Curiosity	MMRTG	1	2011	NASA [56]

Because of the nature of some nuclear forms of power, there is the added benefit of having a thermal regulation system built into the spacecraft. A properly insulated nuclear power source is an ideal source of warmth and heat, which is useful for survival of sensitive instruments in cold sunless environments in the vacuum of space. While there are several safety regulations to consider, especially for missions where the spacecraft are precursors to human colonization, there has been several advancements made in nuclear energy that will allow it to be a safer and more viable option for use in the CubeSat rover. Consider the strides made in making nuclear reactors on craft such as submarines safer. There is no reason to believe that a properly assessed and regulated nuclear reactor cannot be used on a reconnaissance mission in a rover.

5.2.2 Power Systems in Similar Spacecraft

There are other micro-rovers that have been launched or are currently in development that are similar in scope and size to the proposed CubeSat rover. One notable spacecraft is JPL's PUFFER. The Autonomous Pop-Up, Flat-Folding Explorer Robots (A-PUFFERs) are a class of micro-rovers that are meant to study the lunar surface [57]. Applications of PUFFER include mapping the terrain and communicating with other PUFFERS as a swarm when deployed.

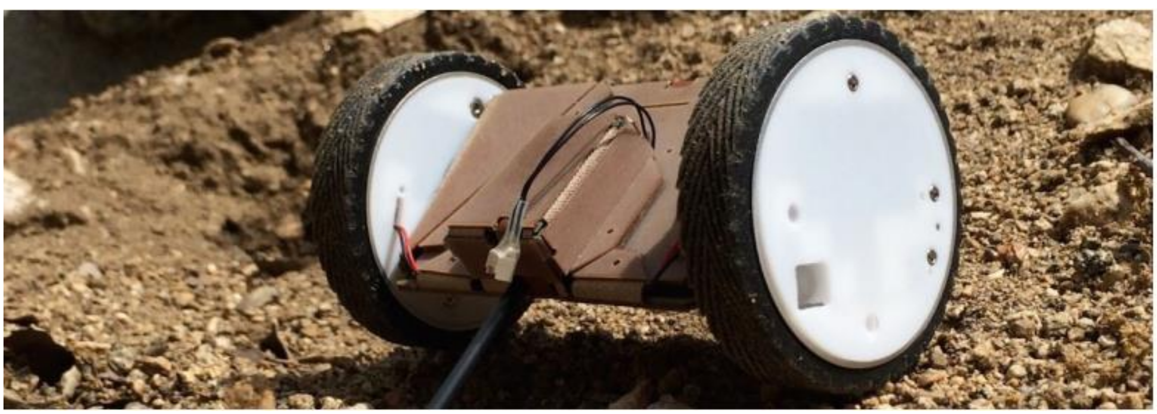

Figure 5.1 PUFFER featured on a testbed [58]

One unique feature of PUFFER is its GaN or Gallium Nitride based converter it uses in its power system. Because of its small size, the rover must efficiently and effectively make use of its available power. The system consequently developed boasts 95% efficiency, and is high-density, very efficient and radiation tolerant as well [58]. This power system has the potential to make micro-rover swarms a widespread solution to otherwise sending one large, more expensive rover in its place. A similar power system can easily be outfitted into a small CubeSat form-factor for use, making the best use of limited resources and space. While the power system has not been commercialized for purchase, what can be gleaned from this design is that smaller, more compact and powerful power systems are a possibility for future micro-rover development.

5.3 Day and Night Rover Design

Because the rover will encounter stark day and night conditions on the Moon, there needs to be constraints for the different conditions considered. This section will outline conditions on the Moon during both day and night, as well as components or

5.3.1 Day Cycle

The moon has day and night cycles of approximately 14 days each [59]. This is an important consideration for the type of power system, and whether insulation or thermal protection is required. Ideally, for a day cycle, a solar panel in tandem with a battery is sufficient to work throughout a lunar day. Because the day is 14 days long, this guarantees near consistent access to sunlight for power. One potential concern however is the presence of lunar dust that may interfere with solar power collection, as well as overheating from the surface temperatures on the Moon; daytime temperatures can reach up to 250 degrees Fahrenheit, which is an important operational consideration.

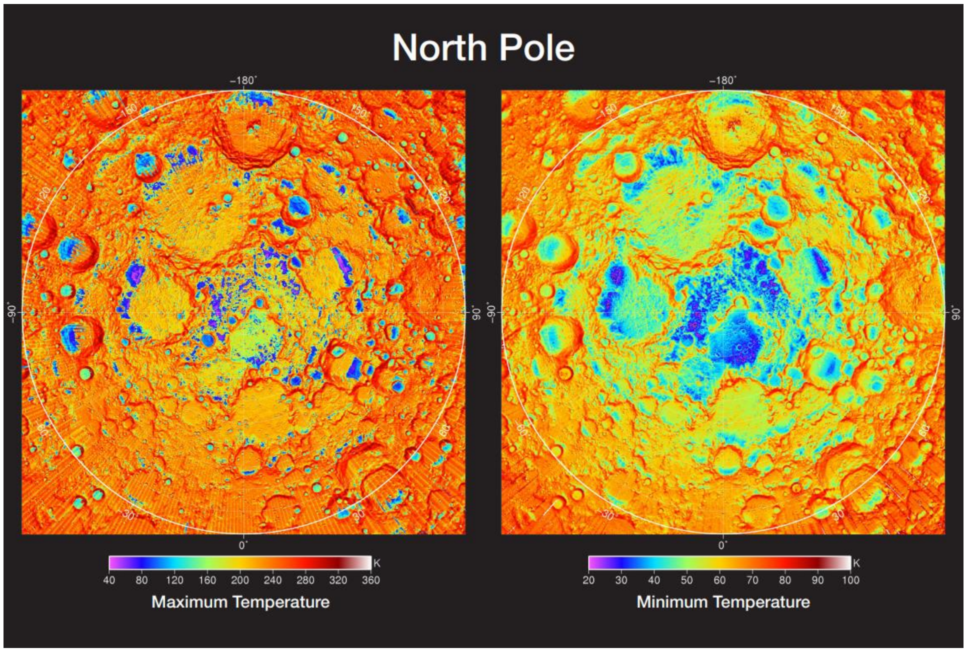

Figure 5.2 - Lunar Reconnaissance Orbiter thermal imaging of North Pole temperature [59]

To summarize the most important design considerations for the day cycle:

1. The rover must have resistance to high temperatures and the proper internal insulation

2. The power system must make full use of the natural resources available for power (i.e., sunlight)

3. There must be a backup power supply in the event of interference from external sources or failure (lunar dust, failure of solar panels)

5.3.2 Night Cycle

Like the day cycle, the night cycle of the lunar day comes with its own set of challenges. Because there is no access to sunlight, there will have to be an alternative source of power aside from solar panels. One consideration is that the rover can be outfitted with nuclear power, much like preceding Moon rovers. An additional advantage of nuclear power is that it becomes a built-in source of heat. This will allow the rover to survive the nighttime temperature of –208 degrees Fahrenheit [59]. If there will be exploration on the lunar poles, temperatures can reach up to –

410 degrees Fahrenheit; exploration could be a possibility as ice water is found at the poles and could be mined as a resource.

To summarize the important design factors for the night cycle:

1. The rover must have a long-lasting power supply other than batteries, such as nuclear power

2. The power system must be well insulated from the cold temperatures present on the lunar surface.

Considering the greatest challenge for the rover is temperature disparity, there must be ways to mitigate the effects of extreme temperatures on the rover's functionality. Some ways to limit this effect include the use of aerogel, gold paint coating, and a thermal regulation system whereby the rover releases excess heat to avoid overheating [60]. With a combination of these thermal regulation techniques, the rover will be better able to withstand the large temperature differences on the surface of the Moon.

5.4 Recommendations

Based on the design constraints and historical data, the best option for the CubeSat rover power system is a solar panel and battery combination with the addition of power converters. Because there is no guarantee of sunlight for the solar panels to collect light in the lava pits, having access to a long-running battery would be the best way for the rover to continuously operate in total darkness and low temperatures. Considering the possibility that speculation of the lava pits being thermally stable turns out to be false, there is no guarantee that the rover will be able to maintain operating conditions in a cold environment outside of operating range, so thermal insulation is a necessity.

While nuclear power is ideal, one possible pitfall of nuclear energy is possible interference with the radiation sensors working properly, which would emphasize the need for proper insulation from sensitive instruments that may otherwise be damaged by the nuclear reactor being included. Additionally, many RTGs are too large to reasonably include on a smaller rover, making them an impractical addition to the power supply. The inclusion of a similar converter system on the rover like on PUFFER would be an ideal way to maximize power output on a smaller battery and limited access to sunlight. Ideally, the battery would just need to last the rover long enough to complete one lunar cycle of 2 weeks Earth time, or 14 days. This will give the rover plenty of time to collect data continuously.

The next chapter will discuss the communications subsystem of the rover, with emphasis on how the rover will establish a comms link with the Lunar Gateway or other similar networks.

Chapter 6

Communications, Guidance, Navigation, and Control

This chapter will cover the comms subsystem, constraints for the system, and approach in the communications for the mission. Recommendations and reasoning for each will be expanded on in this chapter.

6.1 Communications

The crux of the communications system on the CubeSat rover hinges on the deployment of the Lunar Gateway. The gateway will serve as a communications platform between crews on the Moon and Earth, taking full advantage of existing space comms architecture. Figure 6.1 below outlines the gateway architecture:

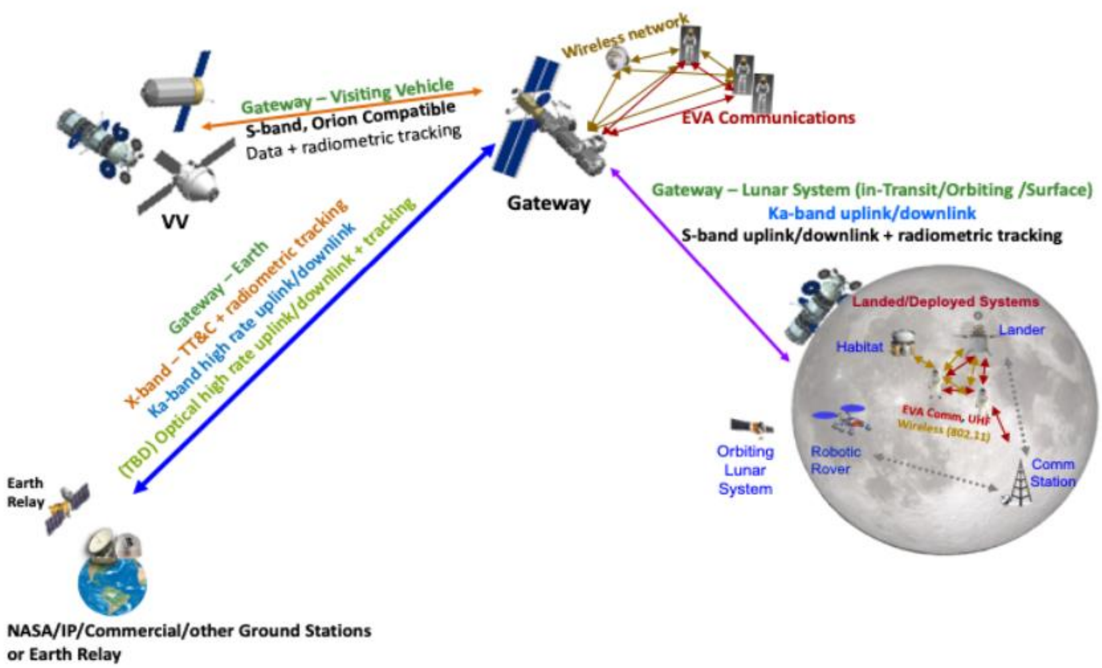

Figure 6.1 - Lunar Gateway architecture visualized [61]

The gateway features Ka-band uplink and downlink capabilities, as well as S-band uplink and downlink capabilities. To take advantage of these resources, the rover comms system will likely consist of a satellite that provides a centralized point of contact for all the rovers, and then will relay the data collected to sources back on Earth or the Lunar Gateway itself. The rovers themselves will need radios on board to effectively communicate with one another to coordinate data collection, and the ability to send data packets to the communications satellite.

On the rover body, the comms system includes a radio, a power source for the radio and an antenna. One of the simplest antennas can even be made from measuring tape. The antenna simply has to be easy to deploy, durable and able to fulfill the comms requirements for the rover to function and send data.

6.1.1 Constraints

A big constraint for the rovers that are exploring the lava pits is that they may not be able to effectively communicate with the comms satellite or one another when blocked off physically. This will require a more complex solution than is presently available and may require several points of contact on the ground that will aid in creating a chain of communication for those rovers. One solution is the deployment of pods across the lunar surface that are specifically meant to aid in building a communication chain or system for each rover to ping continuously.

6.2 Guidance, Navigation and Control

For the GNC system of the rover, the idea is that the rover should be able to traverse the lunar surface automatically. There is technology available to aid in the development of this system, mainly the use of a camera and mapping data for the rover to use while on its mission. This requires two pre-requisites: there must be readily available mapping data from previous scoping of the landing site, and the use of cameras that can help the rover figure out where it's going.

6.2.1 Constraints

The inclusion of a camera that is smart enough to detect hazards and terrain is going to take up substantial computing power on the rover, thus expanding the onboard computers and power system afforded to keep the camera running. Additionally, this poses a problem if the rover finds itself in total darkness, as is the case with lava tubes that may be obstructed from accessing sunlight. An alternative strategy is to create an obstacle detection system with proximity sensors and a limited map of the terrain whenever available. Having a robust communications system will allow the transfer and intake of data needed to accomplish the mission.

6.3 Recommendations

Based on the limited size and scope of the rover, there are a few considerations as to what components to include and what kind of complexity is possible. The spectrometer and atmospheric sensors will already be transferring large packets of data to the Lunar Gateway and subsequently Earth. The addition of cameras or more complex autonomous systems will hinder the nominal function of the rover altogether.

Instead of adding a complex GNC system, it would be better to include sensors such as infrared proximity sensors to aid the rover in readjusting around obstacles. The radio will also be part of a bigger network of radios and comms links that will allow the rovers to effectively communicate with each other and the comms satellite linking it back to the Lunar Gateway.

The next chapter will cover the overall structure of the rover, including the chassis, the location of different subsystems and the overall projected mass and size of the rover.

Chapter 7

Structure

An overview of the structural elements of the CubeSat rover will be discussed in this chapter. A culmination of all the subsystems, as well as materials the rover will be made of will be discussed here.

7.1 Structure Overview

Because the main priority of the CubeSat rover design is to establish the mission scope and subsystems first, the structure will be briefly discussed to accommodate the experiments and other design constraints. This portion of the rover design will not be as comprehensive as the rest of the chapters, but will cover materials, possible structures, and the types of wheels the rover will use.

7.1.1 Subsystem Organization

While the specifics of the rover structure are difficult to pin down at this stage of development, a rough outline of where each subsystem would be located is possible to outline. Assuming the total volume of the rover comes out to be approximately 20U, with a configuration of 2U x 5U x 2U, there will be two levels of structure to outline. A visual of where each subsystem is located is provided below:

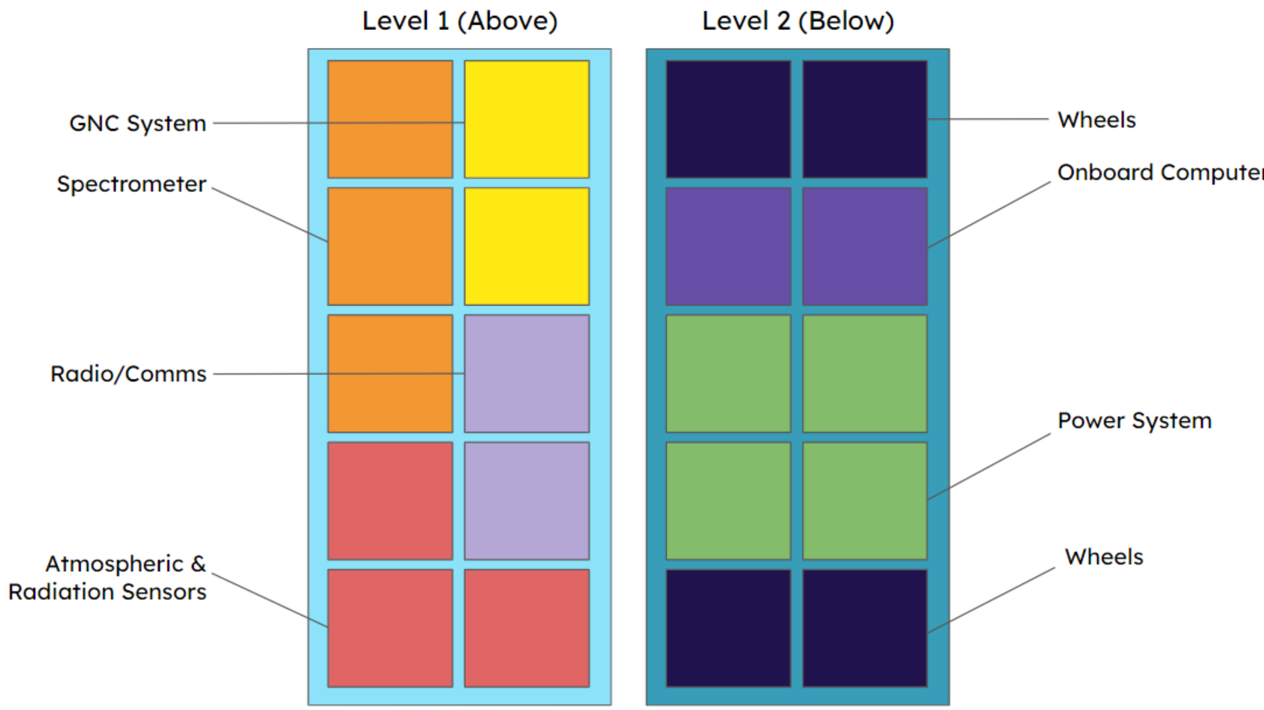

Figure 7.1 - Proposed locations of each subsystem on the CubeSat rover

Each square on Figure 7.1 indicates 1U of CubeSat volume, with the blocks on the left making up the top level of the rover stack, and the blocks on the right indicating the bottom level, or the level closest to the ground when deployed. This is a rough outline, and as improvements in sensor, power, computing, and other technologies improve, this can be further scaled down. The wheels, while stowed, each take up 1U of space. These can then be deployed out from the main body onto the terrain for use.

Modeling the radio and onboard computer after CubeSats such as *TechEdSat*, the radio and computers themselves are powerful enough to be scaled down to the volume shown in Figure 7.1. Generally, these components would not take up more than 0.5U or 1U on a regular 6-12U CubeSat, making the scaled-up volume fit for the rover version.

7.2 Chassis Design

7.2.1 CubeSat Based Structural Frame

Since CubeSats have uniform form-factors, the body of the rover will be designed as a CubeSat. Any protrusions such as the wheels will only be deployed when the rover has landed on the lunar surface. Other considerations such as launch stowage will be based on how traditional CubeSats are stored as payloads on launch vehicles, oftentimes with their own standardized dispensers.

7.2.2 Design Materials

The basis of the chassis or frame of the rover will be an aluminum sheet metal. While other types of frames can be manufactured, aluminum remains light, durable and can be easily modified with cuts and holes to accommodate the hardware inside the frame. This frame is also cost effective, as one large extrusion of aluminum can be cut down and fitted as needed for the flight model. This is the traditional methodology used on *TechEdSat*, which allows the team to quickly manufacture new CubeSats from materials they have on hand.

The wheels may initially be 3D printed for testing and prototyping purposes, and the actual wheels themselves can be custom manufactured with rubber and other durable materials for use on the lunar surface. Taking inspiration from previous Mars missions, the wheels of rovers are typically constructed of titanium frames and rubber wheels to grip the terrain [62]. This is modeled after bicycle wheels generally used on bikes such as mountain bikes on Earth. A similarly designed wheel structure can be constructed from titanium, or aluminum struts as well.

7.2.3 Recommendations

Much of the design will be based on previous CubeSat and rover missions, with an emphasis on a light but strong CubeSat body. This will allow the rover to be modular, cost-effective, and easy to assemble. Using the design philosophy of *TechEdSat*, the rover body can consist of a standardized base body that will allow for easy swapping of different payloads into each individual rover.

Chapter 8
Future Work and Recommendations

8.1 Conclusion

8.1.1 Future Work

While the goal was to establish a developmental baseline of how a CubeSat based rover for lunar exploration would look, the scope was ultimately limited by time constraints and technical expertise. For future work on this design, a comprehensive hardware selection, power system and structure would have to be polished before figuring out any of the detailed calculations for the rover specifications. Additionally, this rover was limited in scope based on the idea that there would be other rovers designed differently in the overall swarm to accommodate other types of research and experiments. While this is just one aspect of research and data collection a lunar reconnaissance mission would entail, there are many other types of research that can be conducted by micro-rovers.

8.1.2 Recommendations

For future development, it is recommended that any team to take on this project break it into a smaller scope that allows each subsystem to be comprehensively developed. This would allow for a better grasp on the technological capabilities of the CubeSat rover form factor, and the structure developed can be more accurately tweaked based on mission specifications. Additionally, due to the author's limited background in power systems and communications, there was missing information and details on the specifications that would make the project a more robust design for development.

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