WAFFLE: Water Analyzer For Future Lunar Expeditions

Team 23

Preliminary Design Review

NASA L'SPACE Mission Concept Academy
Spring 2020

1. Introduction and Summary

1.1. Team Introduction

Name	University (City, State)	Relevant Experience
Timothy (TJ) Carson	University of Redlands (Redlands, CA)	-Sophomore physics major -Experience in robotics, teamwork, communication -Some ability in most areas of physics including thermo, quantum and optics -Interested in instrumentation of spacecraft -Experience organizing teams and brainstorming short and long term goals -Dedicated, can-do mentality and a good problem solver
Devanshi Charadva	Ohlone College (Fremont, CA)	-Freshman computer science major -Experience with C++ -Skilled in communication, project analysis & writing, observation, and planning -Flexible according to the situations -Reliable and responsible team member and always support and respect others
Victor Covasan	California Institute of Technology (Pasadena, CA)	-Senior aerospace engineering major -Experience with rover navigation, guidance and control + satellite instrumentation and data handling -Ability to do anything in the direction of sensing, actuation, computing or electronics -Skilled in Requirements elicitation and hazard analysis; academic report writing with LaTeX -Always delivers before deadline and spends the rest of the time trying to help his colleagues, he often organise hangouts after a successful submission
Veronica Crow	Scripps College (Claremont, CA)	-Senior environmental science major -Experience with data analysis in R, Microsoft Office Suite, research & literature reviews, communications & writing, ArcGIS, and STELLA -Interdisciplinary understanding and approach to projects. -Skilled in planning & management, leadership -Appreciates the diversity involved in any team scenario and how integral it is to success. She knows her own strengths and weaknesses and believes knowing and embracing one's own role is the best way to help one’s team succeed

		-She is also a good mediator, communicator, and problem solver; does a good job of making sure everyone's voice gets heard and all ideas are considered
Sukhdeep Kaur	Ohlone College (Fremont, CA)	-Sophomore computer science -Experience with C++, Python, and Google Spreadsheets -Skilled in Listening, note-taking, planning, designing, and organizing -Able to prepare herself for the presentation, and confident enough to talk in front of million people -Kind to everybody -Always likes to learn something new everyday -Hungry to learn from her team members and ready to collaborate with seniors, mentors, and her team members
Talise Oh	Gavilan College (Gilroy, CA)	-Sophomore physics/math major -Experience with writing & communications, problem space analysis, planning/scheduling, and project analysis -Skilled in organization, schedule management, and good at international trip planning/budgeting. -Ready, able, and willing to work with everyone -Prefers to compromise with others and likes to keep herself on schedule.
Mariana Rodriguez	University of Nevada, Las Vegas (Las Vegas, NV)	-Senior mechanical engineering major -Experience with fluids & heat transfer, kinematic/dynamic calculations, and CAD modeling -Skilled in planning and project management, attention to detail, organization, and graphic design -Worked on numerous hands-on rocketry projects and have experience with leadership roles -She started the rocketry team at her school
Xavier Salcido	University of Redlands (Redlands, CA)	-Senior physics major -Experience with writing & communicating in reports, working with LaTeX, working & communicating with teammates, time management, problem solving,and has a good understanding of physics -Skilled in operation of 3D printers & software, Python, budgeting well, and Microsoft office -Good at working with others and getting the job done. Loves learning from everyone and using his skills to help others as well, and I do some productively and effectively while making sure that everyone feels included
Angelica Shao	Ohlone College (Fremont, CA)	-Sophomore aerospace engineering major -Experience with CAD, Arduino/circuit/breadboards, calculations, and research reports

		-Skilled in Python and C++ -Always get her work done and in on time, and is hardworking academically -Previous leadership experience as president of various clubs and have had a lot of learning moments when it came to organizing, planning, and communicating with various groups of people -Tries to make sure that everyone is heard
Dylan Tabalan	California Polytechnic State University - San Luis Obispo (San Luis Obispo, CA)	-Freshman mechanical engineering major -Experience with CAD modeling, drafting & engineering communications, and shop manufacturing techniques & procedures -Skilled in Microsoft suite, Google Sheets, and planning -Always ready to learn by doing

1.2. Mission Overview

1.2.1. Mission Statement

WAFFLE will determine the viability of lunar water ice as a source for future lunar habitation missions and assess the sustainability of the resource (quantity and distribution). WAFFLE will detect ice and collect quantity and distribution data for analysis, as well as provide a basis for assessments of water quality for study sites of future lunar missions. This mission will provide a new understanding of lunar water ice enabling future lunar and space exploration missions to potentially utilize it as a resource and develop future studies and research questions.

1.2.2. Mission Requirements

1. Launch vehicle, site and date

1.1 Spacecraft constraints

For the lander to be compatible with the launch vehicle and the carrier spacecraft, the following constraints must be obeyed at all times:

WR-MIS-010 The spacecraft shall not exceed 60x60x60cm.

WR-MIS-020 The spacecraft shall not exceed 10kg total mass.

WR-MIS-030 The mission shall be compatible with a launch date on October 15th 2021 from Cape Canaveral, FL.

Additionally, the mission shall obey the following budget limits:

WR-MIS-040 The overall mission budget shall not exceed 35 million US Dollars.

2. Injection, transfer and operational orbits

WR-MIS-050 After launch, the spacecraft shall remain in a low-Earth parking orbit for no more than three days during which the telemetry and all other subsystems will be tested.

WR-MIS-060 The baseline injection strategy shall be to place the spacecraft in an eclipse-free direct transfer trajectory.

WR-MIS-070 A trans-lunar injection shall be performed at arrival, placing the spacecraft in a low lunar orbit of no less than 20km from the lunar surface.

3. Mission phases

WR-MIS-080 The mission phases shall be defined as follows:

0	Pre-launch Phase (Launch Campaign)
1	Launch and Early Operations Phase
2	Commissioning Phase
3	Nominal Mission Phase
4	Extended Mission Phase
5	Decommissioning Phase

3.1 Pre-Launch Phase

WR-MIS-090 Prior to lift-off the spacecraft shall be in an electrically active state and shall be able to perform the following tasks:

- power on/off only via umbilical and without physical access to the spacecraft
- receive telecommande
- handle telemetry packets
- perform on-board monitoring functions

- enter launch mode configuration

3.2 Launch and Early Operations Phase

WR-MIS-100 During launch and until a safe attitude is acquired, all payload systems shall be switched off with the exception of vacuum systems and the spacecraft in a minimal power stage using spacecraft batteries.

3.3 Transfer, commissioning and performance verification phases

WR-MIS-110 The spacecraft shall be released from a polar orbit having a radius of 20km from the lunar surface

WR-MIS-120 The in-orbit laser transmitter shall be released from the Waffle spacecraft TBD seconds after Waffle is released from the carrier.

WR-MIS-130 The main spacecraft shall descend and land to the TBD region of the Shackleton crater.

3.4 Science operation phases

The main science operation phase is defined as the period when the spacecraft is powered by the pre-charged batteries provided for launch.

WR-MIS-140 During the science operation phase the spacecraft shall complete four main science objectives outlined in the Waffle Science Requirements Document:
WR-SCIOBJ-1 to
WR-SCIOBJ-4.

3.5 Extended Operations

The extended operations phase is defined as the period when the spacecraft is powered by the batteries, as recharged by the in-orbit laser transmitter.

WR-MIS-150 During the extended science operation phase the spacecraft shall complete three secondary science objectives outlined in the Waffle Science Requirements Document: *WG-SCIOBJ-5* to *WG-SCIOBJ-7*.

3.6 Decommissioning

WR-MIS-160 The decommissioning phase shall ensure compliance with the Space Debris Mitigation for Agency Projects [AD10].

4 Planetary Protection

4.1 Planetary Protection Requirements

WR-PPR-010 The Waffle mission shall comply with all planetary protection measures listed in The National Environmental Policy Act of 1969.

WR-PPR-020 The Waffle mission shall fulfil the requirements of planetary protection category II.

4.2 Science Contamination Requirements

WR-CON-010 Contaminants or undesired particles (TBD) generated by the spacecraft (e.g. propellant plume, outgassing, etc.) shall have a density lower than 1014 (1013 as a goal) molecules/cm2 on the lunar surface and/or on the collected sample. Typical unwanted contaminants TBD by the science team.

WR-CON-020 The potential contaminants shall be identified, controlled, tracked, documented and readily identifiable from the lunar sample material. The tracking of these contaminants shall start as of the S/C manufacturing process.

WR-CON-030 The spacecraft elements shall cope with the following sterilization and cleaning procedures in order to keep low-levels of forward contamination:

- Alcohol cleaning,
- TBD.

5. Applicable Documents

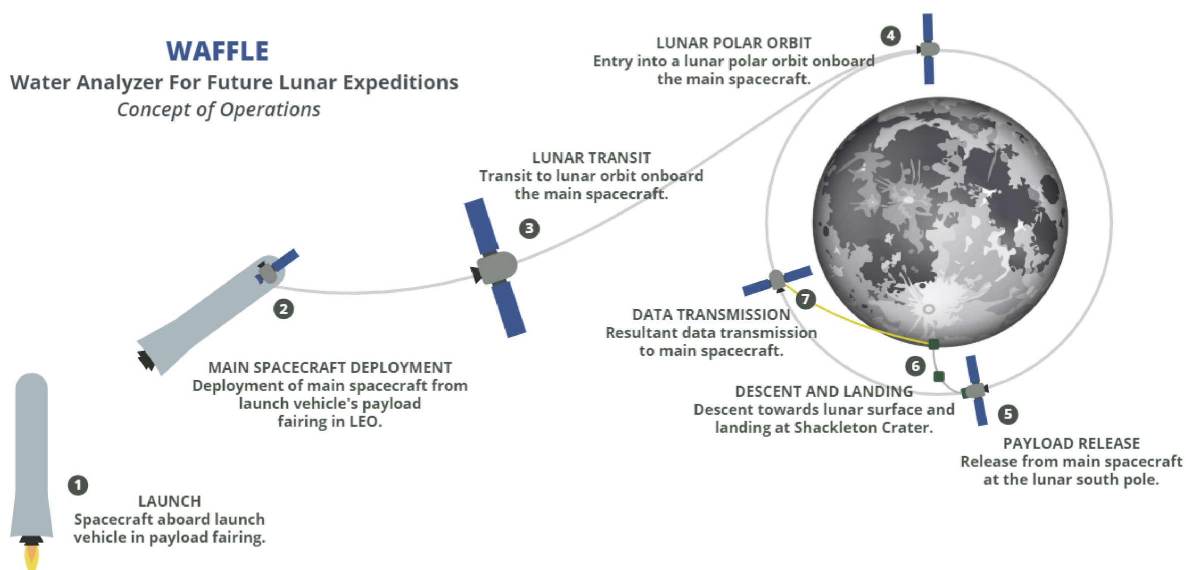
[AD1]	**Waffle-R Science Requirements Document**, [WR-RSSD-RS-001], issue

	1.4, Document providing Science objectives and science requirements, including measurement specifications

1.2.3. Mission Success Criteria

The WAFFLE mission will establish the origin of the Hydrogen signature identified for the Shackleton crater by performing in-situ analysis on the surface regolith. This will be accomplished by means of analysis applied to at least one regolith sample collected over the Nominal Mission Phase. The raw measurements will be uplinked to the Lunar Reconnaissance Orbiter, which will relay it back to the ground station for analysis and processing. The mission will be considered successful if the origin of the H+ isotopes can be determined with less than 10% ambiguity. The existence of Hydrogen in the lunar regolith has been considered indicative of ice water presence by previous investigations performed on data from orbiters, however no conclusive in-situ measurements have been possible so far to prove or disprove this theory. Completion of this main objective corresponds to requirement **WR-SCIOBJ-1** from the WAFFLE Science Requirements Document being met. Additionally, if the presence of water is confirmed during operation, the measurements will be able to also determine the purity of the ice water, therefore assessing its suitability for human settlement support, propellant production or oxygen production. Completion of this secondary objective corresponds to requirement **WR-SCIOBJ-3** from the WAFFLE Science Requirements Document being met.

1.2.4. Concept of Operations

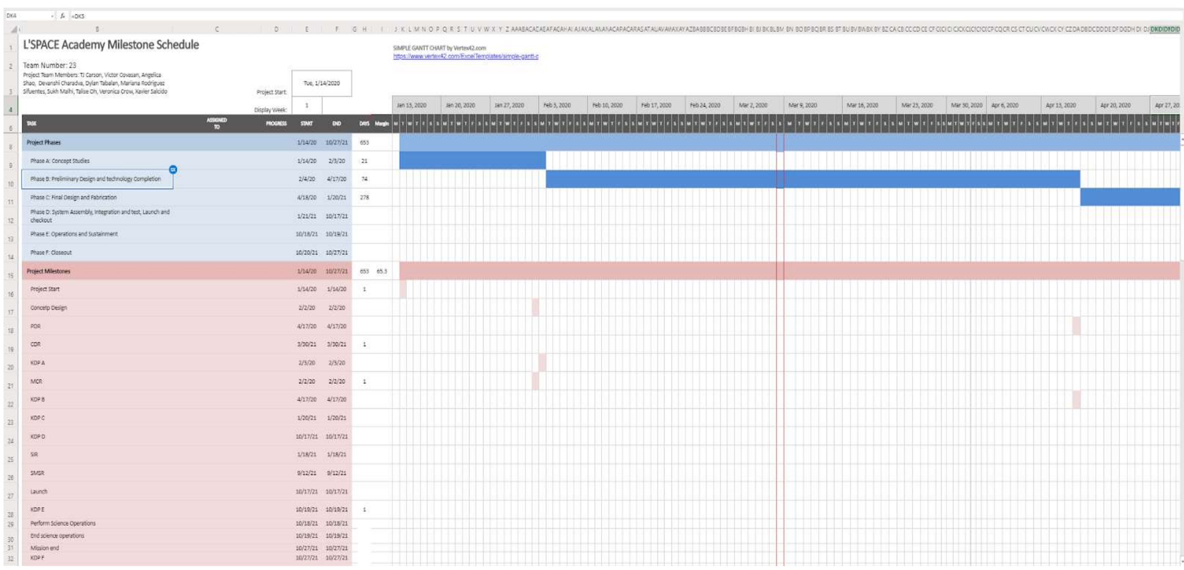


The WAFFLE mission will fulfill its mission statement and objectives via a lunar transit, orbit, and landing path that will allow the collection and transmission of ice water data from the lunar surface. WAFFLE will be a secondary payload aboard a main spacecraft to lunar orbit. The main spacecraft is to be launched into LEO and released from the launch vehicle's payload fairing. At this point, the main spacecraft will begin its lunar transit. This main spacecraft will be placed in a lunar polar orbit once in proximity to the moon.

WAFFLE is to be released as a secondary payload from the main spacecraft. It will independently fulfil its mission objectives while maintaining communications with the main spacecraft. Release of the WAFFLE payload will occur at the south polar region of the moon. WAFFLE will be released to land ballistically at Shackleton Crater.

Upon landing, data collection and analysis will take place at the lunar surface to fulfill the mission's science objectives. Communications with the main spacecraft will allow transmission of the data for final analysis.

1.2.5. Major Milestones Schedule



1.3. Descent and Lander Summary

When the lander has begun its descent towards the lunar surface, cold gas thrusters located near the top of the lander facing outward will induce a spin to gyroscopically stabilize the lander during descent. This will allow a control system onboard to monitor the orientation of the lander and ensure an upright landing. Landing the lander upright is fundamental for successfully orienting the payload to accomplish its mission objectives.

Cold gas thrusters located on the bottom face of the lander will slow the lander near the surface. Prior to landing and upon reaching a predetermined altitude, the thrusters will stop and actuated struts will deploy from the lander in preparation for impact.The struts are designed to absorb shock and vibrations from the impact.

The Lander will perform a powered descent with a descent orbit insertion (DOI) at the North Pole with a forward velocity of 2.38 km/sec at an altitude of 20 km. The lander will then decrease its speed with the thruster to 2.1 km/s performed by a propulsion stage. At an altitude of 15 km, the lander will stabilize the craft with its engines. At an altitude of 7.62 km the lander will begin its burnout phase and should be traveling at a velocity of 0.10729 km/sec. At an altitude of 0.0039624 km, the lander should deactivate its engines and make necessary calculations to be at a velocity of 0.00156464 km/sec. During this phase, WAFFLE should be inside Shackleton crater and touchdown at approximately 0.0044704 km/sec.

1.4. Payload and Science Summary

Instrument	Description	Location in Lander	Deployment Strategy
GNC	The high-precision attitude determination and control system by AAC Clyde. Pointing accuracy is 5 degrees. The GNC will be used to determine position for landing.	Main body	None.
Micro-computer	For water-ice detection processing.	Main body	None.
Comm package	To relay information to the LRO.	Main body	None.
Neutron Spectrometer Subsystem	Two-channel neutron spectrometer to identify hydrogen in the lunar regolith.	Main body	None.
Impact Accelerometer	To detect acceleration at time of impact and provide data for system check.	Main body	None.
Thermal Camera	To detect temperature and temperature	Main body	None.

	differences in the regolith.		
IR Camera	To detect IR signatures of the regolith in conjunction with Thermal Camera	Main body	None.

2. Evolution of Project

2.1. Evolution of Descent and Lander Design

Design 1: In the initial phases of development of the lander design, simplicity of design was prioritized. For this reason, a ballistic lander design was selected which would utilize no form of deceleration upon landing on the lunar surface. This was modelled loosely after the Deep Space lander, and would utilize high-strength materials to shelter the forebody and absorb the momentum of impact at landing. This ballistic lander design was intended to allow the lander to penetrate the lunar regolith to a maximum depth of 1 meter, with the forebody oriented downward and containing instrumentation for direct regolith sampling.
The ballistic lander would consist of a fore-body and an aft-body. The lander would apply a single-stage strategy; there would be no parachutes or airbag-type deployments. Upon landing, the fore-body would penetrate the lunar surface to a maximum of one meter. The forebody would have the shape of a blunted cone. The aft body would have the shape of a half sphere. The weight of the forebody would weigh between 2 to 3 kgs (dependent on the tunable laser diode). The aft body would weigh 2 to 3 kg. The aeroshell would weigh less than 2 kg.

Design 2: Upon further analysis and more detailed selection of instrumentation, the lander design was adjusted to address new concerns. Firstly, the ballistic payload approach did not adequately address the need to control the orientation of the lander to ensure that instrumentation was appropriately located and deployed upon contact with the lunar regolith. To resolve this, a method for gyroscopic stabilization was developed to be deployed during descent using thrusters. Design 2 did not allow room for additional maneuvering once landed.

Design 3: During the development of the science experiments, the Science Team considered sampling of the regolith at various locations in the vicinity of the landing site. The ballistic approach did not provide a suitable method to move the lander after impact, especially if it penetrated the lunar surface. For this reason, a soft-landing was selected as seen in Design 2. In Design 3, the landing method was further modified to introduce a soft landing facilitated by thrusters and struts, both of which would be deployed once the lander has reached a predetermined altitude. A soft landing allowed for mitigation of the vibrations induced upon impact. The thrusters and struts would also be used to “hop” the lander to other locations within the crater.

2.2. Evolution of Payload

In the earlier stages of planning, the Science Team considered a range of instruments including tunable laser diodes, the Near-Infrared Volatile Spectrometer Subsystem (NIRVSS) instrument, and the Neutron Spectrometer System (NSS). After careful review of instrumentation, the Science Team made the initial decision to include a modified NIRVSS instrument aboard the WAFFLE lander. Research was done to determine the mass of the instrument, dimensions, and cost. The Science Team was unable to precisely pin down exact dimensions of a subcomponent of the NIRVSS instrument. The inability to locate a drill to pair with the NIRVSS instrument to fit within mass and size requirements posed a challenge. In detail, the smallest drill from Honeybee Robotics would weigh 1 kilogram, cost unknown. The instrument package itself would weigh 3.1 kilograms. The spectrometer system in total would weigh 4.1 kg, or 41% of the specified payload weight.
The Science Team has since decided to move forward with the NSS instrument. The Neutron Spectrometer System weighs 1.6 kilograms to include the sensor and processing module. No drill is needed to obtain samples. The instrument will measure the presence of water up to a depth of 100 cm.

The following table includes the initial instrumentation for the lander. The instrument highlighted in red has been replaced with the NSS instrument.

Instrument	**Description**	**Location in Lander**	**Deployment Strategy**
GNC	The high-precision attitude determination and control system by AAC Clyde. Pointing accuracy is 5 degrees. The GNC will be used to determine position for landing.	Aftbody	None.
Micro-computer	For water-ice detection processing.	Aft body	None.
Comm package	To relay information to the LRO.	Aft body	None.
Water-Ice Simple Examiner (WISE)	Tunable laser diode with sample collection chamber.	Forebody	Umbilical cable/spring.

Impact Accelerometer	To detect acceleration at time of impact and provide data for system check.	Forebody	Umbilical cable/spring.
Temperature Camera	To detect temperature and temperature differences in the regolith.	Forebody	Umbilical cable/spring.
IR Camera	To detect IR signatures of the regolith in conjunction with Thermal Camera	Main body	None.

2.3. Evolution of Mission Experiment Implementation Plan

The first payload design would introduce the tunable laser diode as the primary science instrument aboard the lander. The tunable laser diode would be used to measure and detect the presence of water *in situ*, utilizing the ballistic approach of Design 1 (outlined in Section 2.1) to obtain a physical sample of the regolith. The experiment was designed to meet all scientific requirements and goals. Upon further research, concerns relating to precision and accuracy of the tunable laser diode arose.

The second iteration of payload introduced the NIRVSS instrument as the primary science instrument aboard the lander. The NIRVSS instrument's range of capabilities allowed for an expansion of science experiments and data-gathering. The NIRVSS instrument's spectrometer can differentiate between water and hydroxyl and identify the presence of frozen carbon dioxide, ammonia, and methane. The Science Team expanded the science objectives to include presence of other minerals and frozen materials. Conversely, there was a limiting factor introduced by the NIRVSS system. The NIRVSS instrument relies on a drill sample taken from a predetermined depth of the lunar regolith. Weight limitations did not allow a drill long enough to penetrate 1 meter into the regolith. The Science Objectives were modified to exclude confirmation of water-equivalent hydrogen at a depth of 1 meter due to the limited range of the drill.

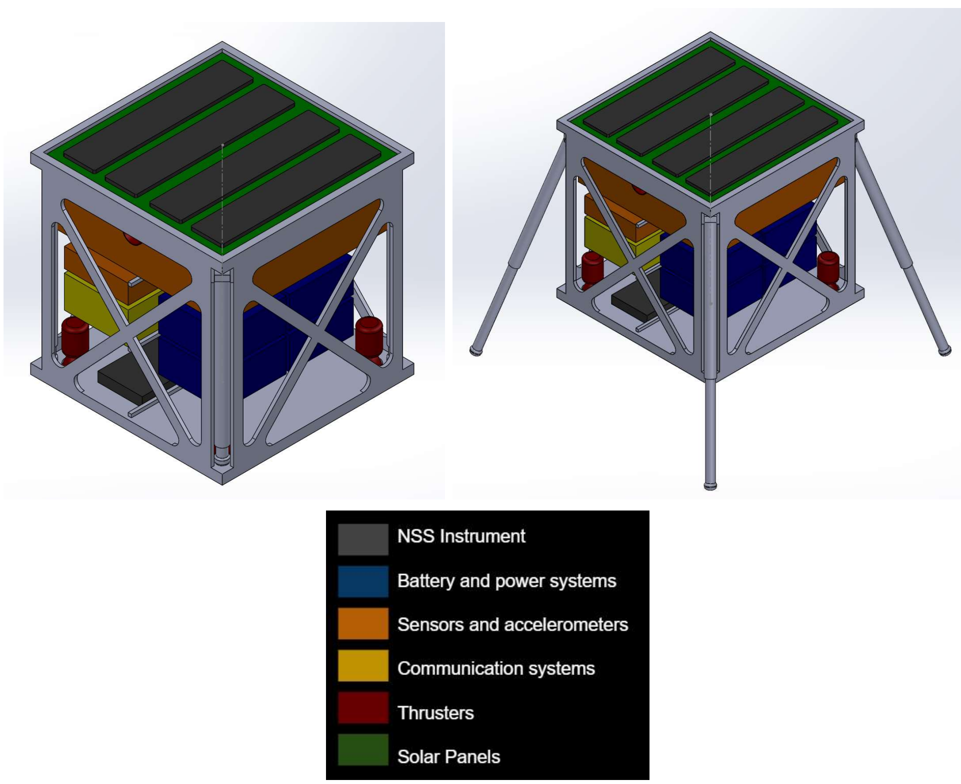
The third iteration of payload saw improvement to the Science Objectives. The NIRVSS instrument was replaced by the NSS, a much lighter, less costly, and deeper-penetrating instrument. The NSS does not require use of a drill to detect the presence of water-based hydrogen. The NSS can detect water-equivalent hydrogen down to 1 meter in depth. The Science Objectives were modified to include confirmation of water-equivalent hydrogen down a depth of 1 meter.

3. Descent and Lander Design

3.1. Selection, Design, and Verification

After deployment and once the lander has begun its descent towards the lunar surface, cold gas thrusters located near the top of the lander facing outward will induce a spin to gyroscopically stabilize the lander during descent. This will allow a control system onboard to monitor the orientation of the lander and ensure an upright landing. Landing the lander upright is fundamental for successfully orienting the payload to accomplish its mission objectives.

A soft landing system was selected for the mission. The lander has been designed for a soft landing to protect onboard instrumentation and sensors.



Cold gas thrusters located on the bottom face of the lander will slow the lander near the surface. Prior to landing once reaching a predetermined altitude, the thrusters will stop and actuated struts will deploy from the lander in preparation for impact.The struts are designed for absorbing shock and vibrations from the impact. The cubic structure of the lander and incorporation of the strut was chosen to optimize our usage of the volume constraints. Diagrams above show the lander in its descent configuration (top left) with the struts collapsed into the structure, as well as the lander in its landing configuration with the struts deployed (top right).

3.1.1. System Overview - N2 Chart

From a systems perspective, the whole spacecraft is an input-output system that intakes a regolith samples and returns raw digital values that can be mapped to a range of materials and substances. The N2 Chart helps visualise the inner-workings of such a system by expanding only the components that have a bearing on the final output. As a result, the technology enabling the mission is abstracted and only the path followed by the data from collection to publication is being observed.

Figure 3.1.1 illustrates this path by focussing on where the processing is being performed: onboard the spacecraft, which is referred to as Online Processing, or offline - at the ground station. The first three online processes are handled entirely by the NSS instrument, that first thermalises the regolith sample within its chamber, then an analog transducer is used to convert the emitted neutron flux into an analog voltage. The signal is then chopped into discrete pulses that are transmitted asynchronously through the RS-422 protocol(full-duplex). The pulses are then captured by one of the interrupt pins of the RAD750 microcontroller and stored until the next uplink window. The stored signal is augmented with checksum measures and encrypted; this is to reduce the possibility of attenuation or data loss during transmission. The signal is then uplinked to the LRO which would relay it back to Earth.

The measurements are then picked up by the Deep Space Network and stored as Level 0 Data. After additional filtering, smoothing, interpolation and other noise reduction measures aiming to eliminate the sensor bias or drift from the raw signal, the measurements are stored as Level 1 data. A second team of scientists then analyse the processed measurements for consistency against known physical constants or metamorphic relations as a means of correlation and validation. The measurements that pass this test are made available to the public as Level 2 Data, together with Data Package Instructions describing how to access the separate variables or properties of the signal. Finally, the conclusions drawn by the mission scientists are published, together with a thorough discussion of the nature of lunar regolith, and potentially water ice, in the Shackleton crater.

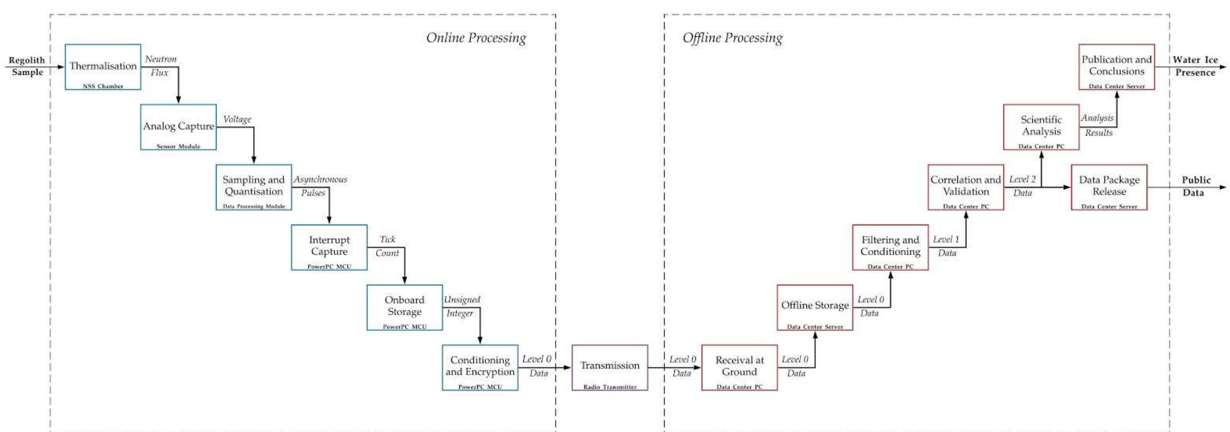


Figure 3.1.1: N2 Chart for the Waffle Data Package

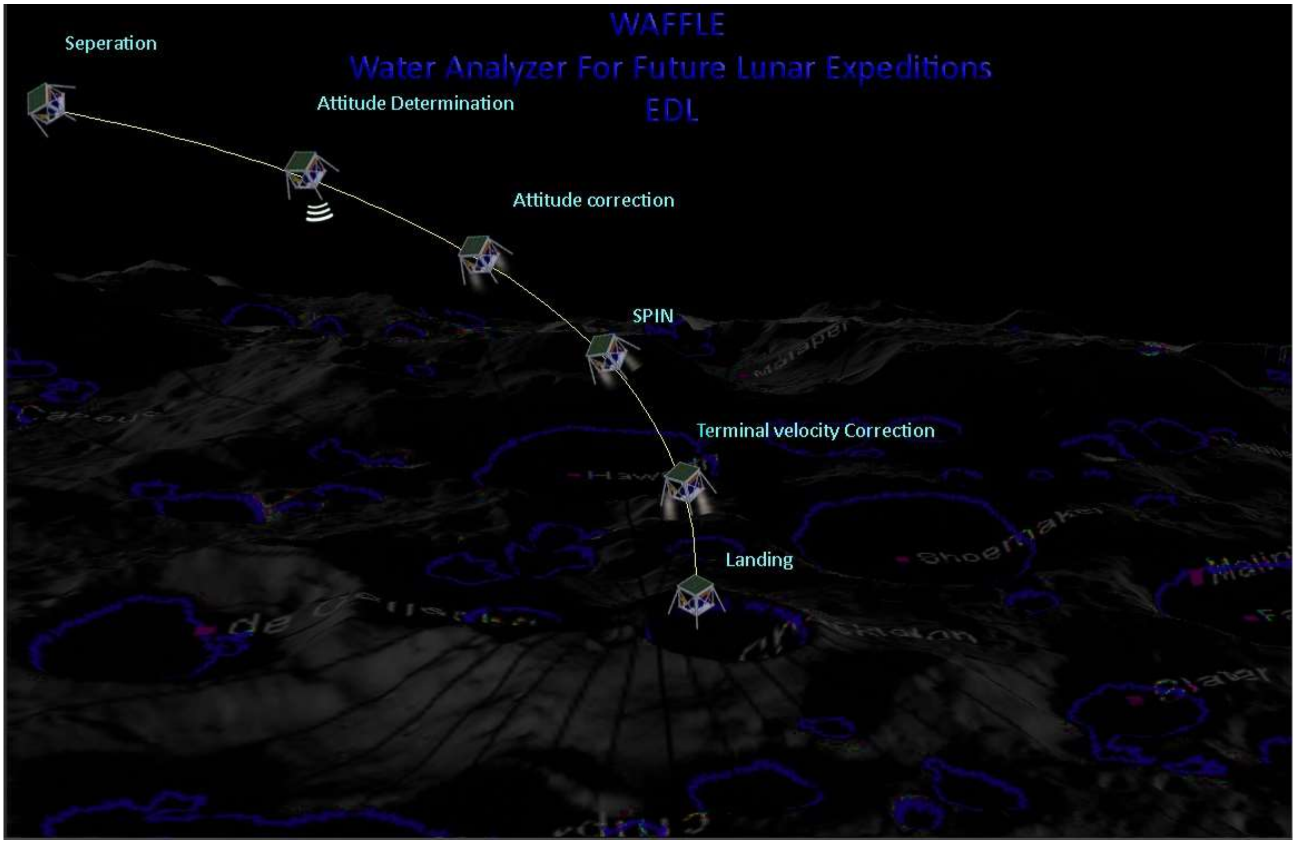
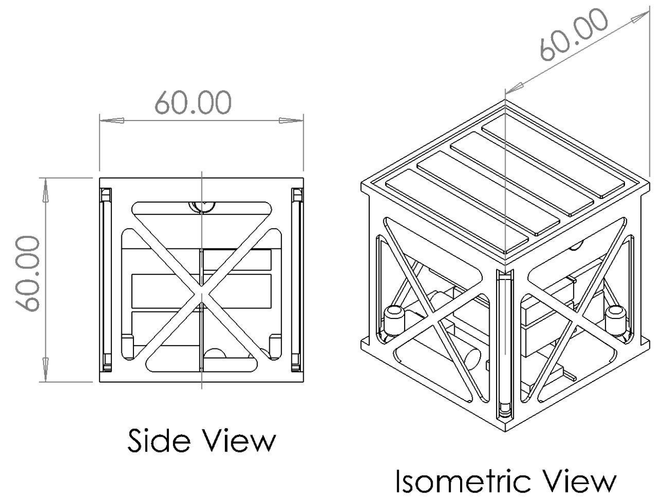


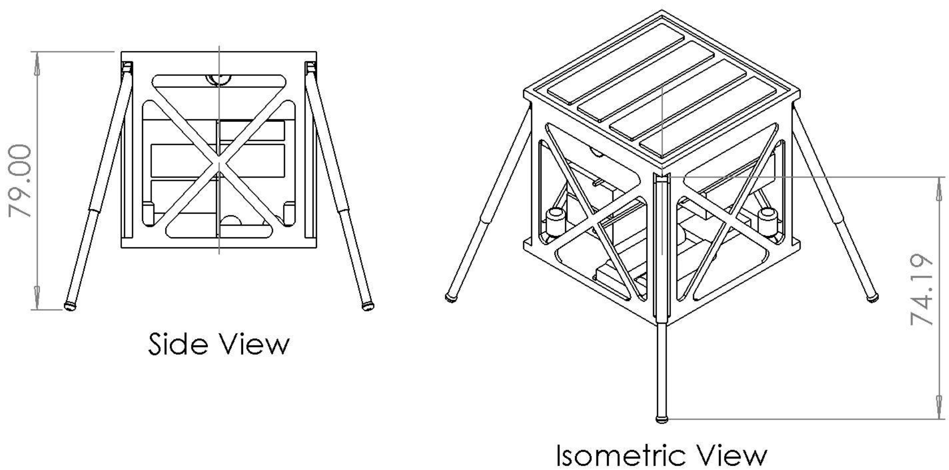
Figure 3.1.1.2 EDL Graphic for WAFFLE

Descent and Landing System:

The spacecraft is equipped with two thruster belts, the upper one acting as a Reaction Control System(RCS) for attitude stabilisation, while the second one is used for descent control and slow-down. Cold gas thrusters located near the top of the lander facing outward will induce a spin to gyroscopically stabilize the lander during descent, once the RCS system aligns the spacecraft with the true nadir direction. Cold gas thrusters located on the bottom face of the lander will slow the lander near the surface. Prior to landing, once reaching a predetermined altitude, the thrusters will stop and actuated struts will deploy from the lander in preparation for impact.The struts are designed for absorbing shock and vibrations from the impact. In the extended mission phase, the remaining thrusters will be used to “hop-around” and explore different parts of the crater.

CAD model:





3.1.2 Thermal Design:

- ***Spacecraft Thermal Control:***

Thermal control is essential in spacecraft design. In spacecraft design, thermal design components are beneficial that improve the overall performance. To be successful in any space mission, we need to make sure our system is protected. For example, how to protect the equipment from overheating? How to protect the equipment from unusual temperatures? There are major key components that protect the spacecraft from overheating or cooling.

a. ***Thrusters***

Thruster is a propulsive device used by spacecraft for station keeping, attitude control, in the reaction control system, or long-duration, low-thrust acceleration. A **vernier engine** or **gimbal engine** is a particular case used on launch vehicles where a secondary rocket or other high thrust device is used to control the attitude of the rocket while the primary thrust engine (generally also a rocket engine) is fixed to the rocket and supplies the principal amount of thrust.

Some devices that are use or proposed to use as thrusters are:

- Cold gas thruster
- Electrohydrodynamic thruster, using ionized air (only for use in an atmosphere)
- Electrodeless plasma thruster, electric propulsion using ponderomotive force
- Electrostatic ion thruster, using high-voltage electrodes
- Hall effect thruster, a type of ion thruster
- Ion thruster, using beams of ions accelerated electrically
- Magnetoplasmadynamic thruster, electric propulsion using the Lorentz force
- Pulsed inductive thruster, a pulsed form of ion thruster
- Pulsed plasma thruster, using current arced across a solid propellant
- RF resonant cavity thruster, an electromagnetic thruster using microwaves
- Rocket engine, using exothermic chemical reactions of the propellant(s)

b. ***(a)Sinks: deep space***

Deep space exploration (or **deep-space exploration**) is the branch of astronomy, astronautics and space technology that is involved with exploring the distant regions of outer space.[1] However, there is little consensus on the meaning of "distant" regions. In some contexts, it is used to refer to interstellar space. The International Telecommunication Union defines "deep space" to start at a distance of 2 million km from the Earth's surface. NASA's Deep Space Network has variously used criteria of 16,000 to 32,000 km from Earth. Physical exploration of space is conducted both by human spaceflights (deep-space astronautics) and by robotic spacecraft.

At present the farthest space probe mankind has constructed and launched from Earth is Voyager 1, which was announced on December 5, 2011,[2] to have reached the outer edge of the Solar system,[3] and entered interstellar space on August 25, 2012.[4] Deep space exploration further than this vessel's capacity is not yet possible due to limitations in the space-engine technology currently available.

Some of the best candidates for future deep space engine technologies include anti-matter, nuclear power and beamed propulsion.[5] The latter, beamed propulsion, appears to be the best candidate for deep space exploration presently available, since it uses known physics and known technology that is being developed for other purposes.[6]

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c. *Storage*

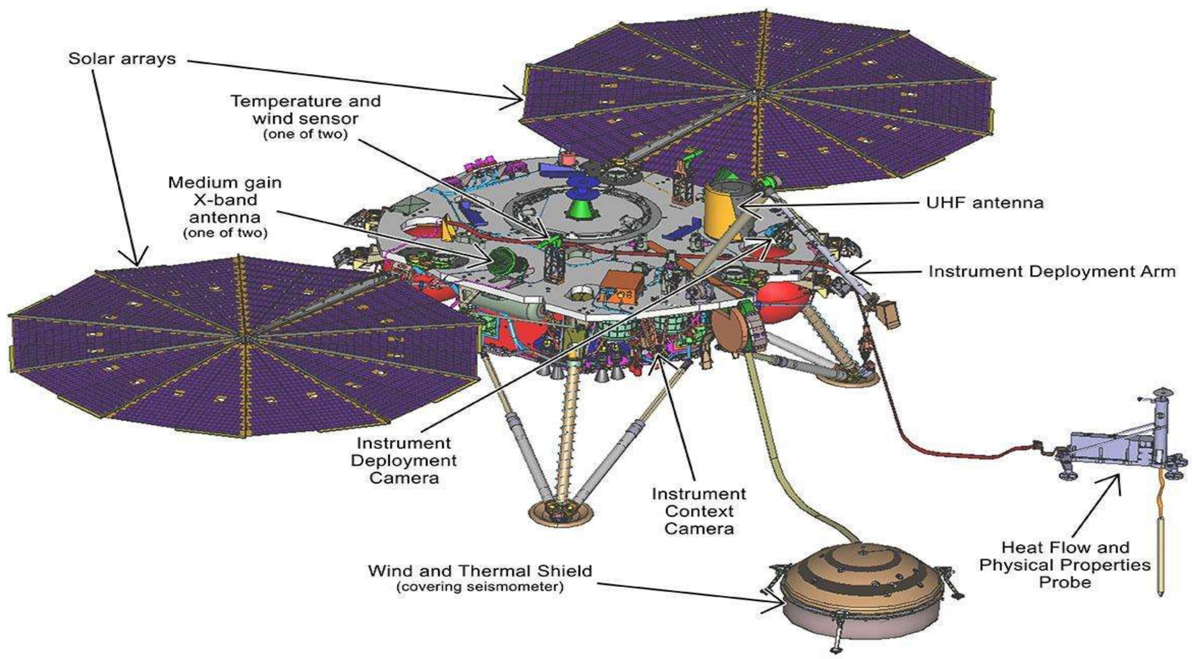
1. The electric energy storage options for space missions include batteries, regenerative fuel cells, and flywheels.This area considers these methods of storing energy after it has been generated from solar, chemical, and nuclear sources if the energy is not needed immediately.
    a. *Batteries*: Advancements in lithium-based and other battery chemistries (both primary and secondary and particularly in terms of specific energy and safety) are required to support the broad range of NASA missions: science, human exploration, and aeronautics.
    b. *Flywheels:* Once materials challenges are met, flywheel technology can offer energy storage density on par with chemical batteries with much higher cycle life. They can also offer spacecraft a novel system for combining attitude control (replacing momentum

wheels) and energy storage (replacing batteries), reducing the overall mass of the combined systems.

c. *Regenerative Fuel Cells:* Regenerative fuel cell technology, in either solid oxide or proton exchange membrane chemistry, offers large-scale energy storage at specific energy levels well beyond that possible with chemical batteries.

d. *Capacitors*: A capacitor is a passive, two-terminal electrical component used to store energy electrostatically in an electric field. Capacitors can provide pulse power capability at low temperatures for spacecraft and avionics.

The spacecraft could have the following equipment including cameras, sensors etc.



3.1.2. SubSystem Overview

Except for the NSS instrument, which is the core of the spacecraft, a multitude of subsystems are designed to be supportive of the scientific objectives. Among these, a propulsion and attitude control system, the power management system, data handling etc. The interactions and interdependencies between these are intricate; Figure 3.2.1 helps visualise the relations between the six main subsystems of the WAFFLE mission.

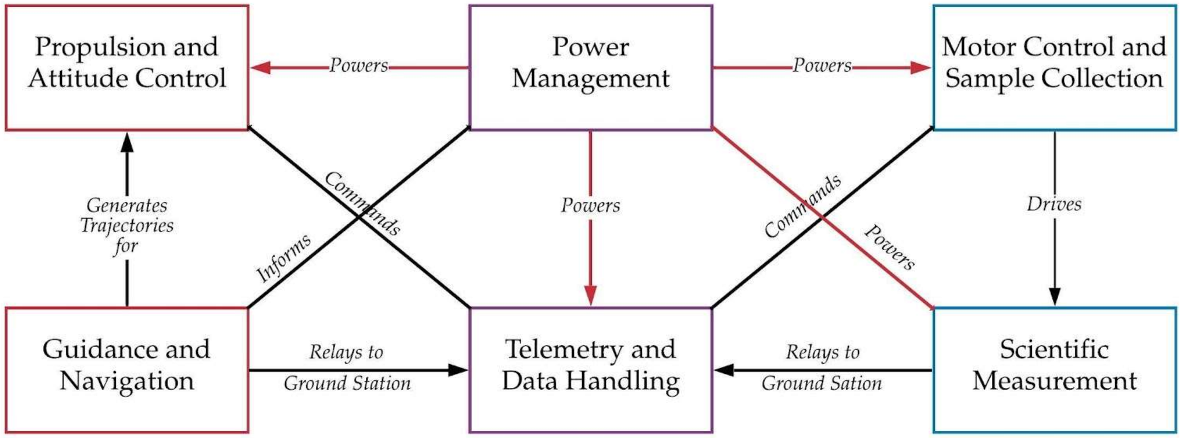


Figure 3.2.1: Main Spacecraft Subsystems and the Interactions Between Them

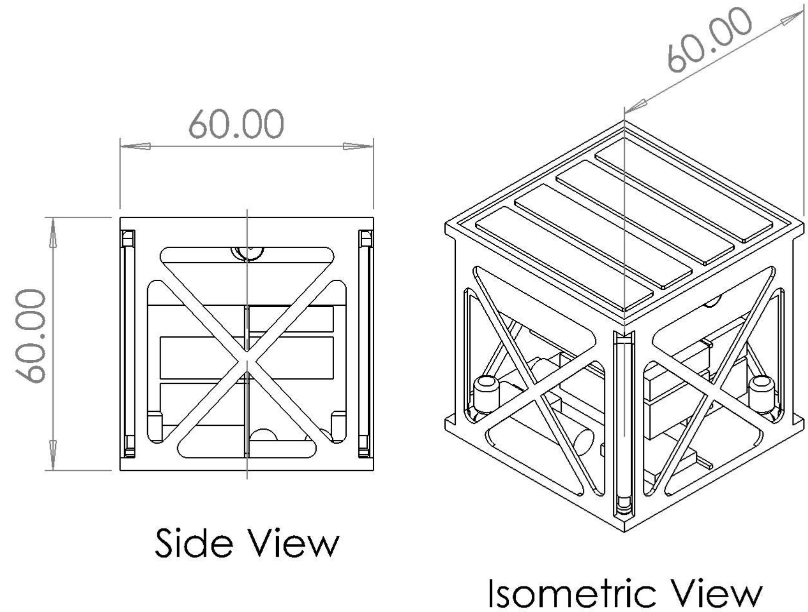
First, the power management system (PMS) powers all other subsystems, except for GNC, which has its own power supply. On the other hand, the GNC informs the PMS during hazardous mission phases to cut the power towards sensitive instruments, to ensure low risk of electrical damage or spikes.

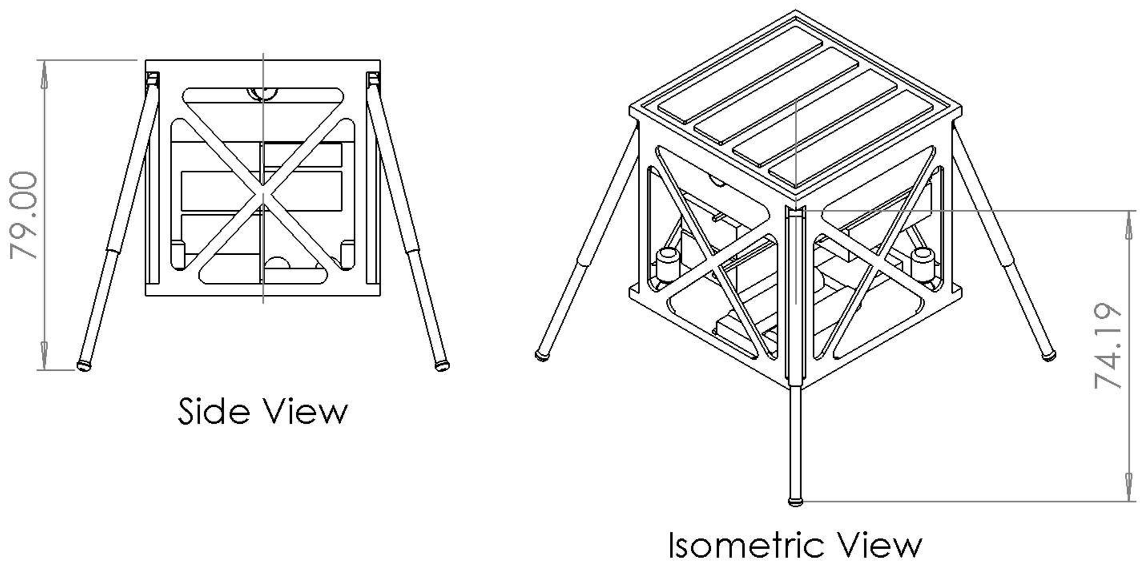
The telemetry and data handling(TDH) subsystem contains the PowerPC RAD750 microcontroller which is used to command the propulsion system and motor controller based on position estimates received from the GNC. The TDH is used both to transfer information and commands between non-communicating subsystems and for communication with the ground station, measurement storage or caching.

The brushed DC motor actuates the drill that provides the regolith samples to the NSS instrument but it also spins the navigation platform which contains the star trackers, together with the infrared and thermal cameras. This is an energy-efficient way of generating 3D profiles of the area surrounding the impact crater.

3.1.3. Dimensioned CAD Drawing of Entire Assembly

Below are dimensioned drawings of the assembly in its descent and landing configurations. All dimensions are in units of centimeters.





3.1.4. Manufacturing and Testing Plans

The WAFFLE team will outsource the manufacturing of the lander's mechanical structure to Space Application Services(SAS), which is a company experienced in manufacturing medium-cost lunar equipment. The NSS instrument will be outsourced to Lockheed Martin for production. Thrusters will be supplied by Aerojet Rocketdyne, who can provide compact 3D printable titanium alloy thrusters, this way minimising the weight and reducing stress condensation due to less linking mechanisms. Thermal Imaging Cameras and IR Cameras will be manufactured and bought from Thermoteknix. All onboard computers and microprocessors will be provided by PowerPC, who offer a wide range of products, suitable for purposes varying from filtering or data handling to autonomous navigation capabilities. During a span of 10 months from January to October, all subsystems will have been delivered by contractors, so assembly, integration and testing will be carried out by the team at NASA GSFC. There will be several tests simulated such as a static load test or simulated aerodynamic and inertia loadings, vibration and shock testing, thermal environment testing, and simulated vacuum environment simulations, radiation dose testing that will be performed on all the components of the WAFFLE Lander both individually and integrated.

3.1.5. Validation and Verification Plans

Table C-1 shows an example of what our validation matrix would look like for each component of WAFFLE including testing, analysis, inspection and demonstration.

Table C-1 Validation Requirements Matrix

Validation product #	Activity	Objective	Validation Method	Facility or Lab	Phase	Performing Organization	Results
Identifier for validation product	Describe evaluation by the customer/sponsor that will be performed	What is the meaning of the sponsor evaluation?	Validation method for the requirement (analysis, inspection, demonstration, or test)	Facility or laboratory used to perform the validation	Phase in which the verification/ validation will be performed	Organization responsible for coordination the validation activity	Indicate the objective evidence that validation activity occurred
1	Sponsor will confirm that the lander is up to standards and has passed necessary tests.	Ensure that the sponsors money is well invested in the lander through its appearance and presentation	Test	AMES	Phase C	WAFFLE TEAM	NSS Test 1

Table C-2 shows an example of what our verification matrix would look like for each component of WAFFLE including testing, analysis, inspection and demonstration.

Table C-2 Verification Requirements Matrix

Requirement No.	Document	Paragraph	Shall Statement	Verification Success Criteria	Verification Method	Facility or Lab	Phase	Acceptance Requirement?	Preflight Acceptance?
Identifier for validation product	Document # the requirement is contained within	Paragraph # of the requirement	Text of the requirement , the “shall”	Success criteria for the requirement	Verification method for the requirement	Facility or lab used to perform the validation and verification	Phase in which the verification and validation will be performed	Indicate whether this requirement is also verified during initial acceptance testing of each unit	Indicate whether this requirement is also verified during any pre-flight or recurring acceptance testing of each unit.
X-1	xxx	Ex. Section 2.2.1.1 Comm package	Comm package shall downlink the data from WAFFLE to NASA headquarters.	Data package received at NASA headquarters approximately 20 minutes after landing.	Analysis	Facility	Phase E	X	X
X-2	xxx	other info.	Other shall statements	etc.	xxx	xxx	xxx	xxx	xxx

3.1.6. FMEA and Risk Mitigation

Risk	Likelihood	Effect on Project	Mitigation
Digital Team posing risk in lack of communication, Unrelated information/missed details, and social disconnection	Medium	Low	Clearly relay information to everyone on the team and provide written text or images that clearly relay this information.
Landing Failure	Medium	Medium	Accept
Key Employee encounters emergency/ illness	Medium	Low	Train employees before to step in and take over a role in case of emergencies. Allow for a few days spare time in case. Thorough documentation and tracing for each work package.
Loss of critical personnel.	Medium	Medium	Ensure that personnel can take over if someone leaves.
Lander or Descent system damaged during transportation or during launch.	Medium	High	Secure Lander or instruments safely onboard the transportation system. Have spares parts if possible for vulnerable pieces.
Missing targeted landing zone	Medium	Medium	Recheck orbital mechanics, and ensure proper calibration of the GNC instruments.
Structural damage during landing	Medium	High	Research the material necessary to withstand the forces that it may undergo.

			Perform vibrational and force testing.
Descent system damaged during landing	Medium	High	Perform vibrational and force testing. Securely fasten the thrusters to the body of the lander. Additional damping mechanisms.
Descent system damaged during transportation	Medium	High	Provide safety guidelines for handling the lander to include descent systems.
Thrusters failure.	High	High	Thoroughly plan and schedule ahead to ensure functionality of the thruster system. Ensure that the provider is reliable.
Lander Incomplete/Design flaw	Medium	High	Plan and Stay ahead of schedule. Redundancy and flexibility through software.

3.1.7. Performance Characteristics and Predictions

The WAFFLE mission will establish the origin of the Hydrogen signature identified for the Shackleton crater by performing in-situ analysis on the surface regolith. This will be accomplished by means of analysis applied to at least one regolith sample collected over the Nominal Mission Phase. The raw measurements will be uplinked to the Lunar Reconnaissance Orbiter, which will relay it back to the ground station for analysis and processing. The mission will be considered successful if the origin of the H+ isotopes can be determined with less than 10% ambiguity. The existence of Hydrogen in the lunar regolith has been considered indicative of ice water presence by previous investigations performed on data from orbiters, however no conclusive in-situ measurements have been possible so far to prove or disprove this theory. Completion of this main objective corresponds to requirement **WR-SCIOBJ-1** from the WAFFLE Science Requirements Document being met. Additionally, if the presence of water is confirmed during operation, the measurements will be able to also determine the purity of the ice water, therefore assessing its suitability for human settlement support, propellant production or oxygen production. Completion of this secondary objective corresponds to requirement **WR-SCIOBJ-3** from the WAFFLE Science Requirements Document being met.

3.1.8. Confidence and Maturity of Design

In section 3, Descent and Lander, we focused on what our lander would need to make our mission successful. As seen in section 3.1.3, the CAD drawing visually represents our final model of WAFFLE. WAFFLE started off with a nose cone design where the lander would essentially crash slowly, but fast enough into the regolith to puncture the surface. WAFFLE was supposed to be a ballistic lander consisting of a fore-body and an aft-body. The lander would apply a single-stage strategy; there will be no parachutes or airbag-type deployments. Upon landing, the fore-body would penetrate the lunar surface to a maximum of one meter. The forebody would have the shape of a blunted cone. The aft body will have the shape of a half sphere. The weight of the forebody would weigh between 2 to 3 kgs (dependent on the tunable laser diode). The aft body would weigh 2 to 3 kg and the aeroshell would weigh less than 2 kg. The flaw we had with this design was that we didn't know how to properly manage the structure of the blunt cone design, as well as problems encountered during the hopping method where we would essentially move around inside the crater, because we would have to figure out a way to dig yourself out of the regolith and penetrate the surface again. In order to ensure that our lander would have a higher chance of success than our original design, we went with a more traditional lander design as seen in section 3.1.3. The new design for WAFFLE contains 2 thrusters located on diagonal sides, four landing struts and a body encasing equipment, instrumentation and computers.

From an engineering point of view, the overall confidence of the mission depends mainly on the successful completion of two milestones: precise guidance during the EDL phase and the successful deployment of the NSS instrument once safely on the surface. To complete the first milestone, robust feedback control systems are essential. First, during EDL stabilisation, it was not considered sufficient to rely on the inertial position estimates provided by the IMUs, but the system was augmented with star-tracking cameras and accelerometers operated as gravity gradient sensors for offset cancelling and absolute referencing. The fusion between all these provides a reliable estimate of the true nadir direction, which upon reached, a Proportional-Integral-Derivative(PID) controller will actuate the thrusters and stabilise the spacecraft gyroscopically. This methodology is expected to deliver offset-free tracking of the true nadir direction, after separation from the carrier spacecraft due to the combination of short-term attitude control upon separation and passive spin stabilisation during descent.

For the second milestone, however, the same performance can hardly be guaranteed at the current stage. Since safe landing involves an equal combination of structural reliability and precise control, the necessity for extensive simulation and validation becomes apparent. Specifically, it is desirable that during the final descent stage the lander is not slowed down too much, but retains sufficient forward speed and angular momentum to dig into the surface and remain upright for the remainder of the active science phase. It is the balance between these two conflicting requirements that is most difficult to guarantee: that the spacecraft will be able to land in a controlled manner and with enough forward velocity while digging enough into the regolith and not destroying the nose fairing at impact. Luckily, the lunar literature abounds with studies on changes in regolith properties with temperature or compression, which would allow the team to run extensive simulations and find the right balance of controls and material properties that would guarantee safe landing.

3.2. Recovery/ Redundancy System

The redundancy and safety measures built into the spacecraft architecture can be divided into: processing, communication, interfacing, and software. First, the Integrated Navigation Package provides three levels of redundancy in terms of sensors and conditioners, therefore the raw sensor measurements can be voted and averaged to increase the reliability of the final measurement. The navigation computer(NC) is equipped with WatchDog timers that can be configured to monitor for scheduling conflicts in the Real-Time Operating System.

To mitigate radiation hazards such as Single-Event Effects, redundancy in the communication buses between the computing units and their peripherals were added, such that if any channel suffers a rupture after contact with energetic particles, the sensor remains accessible. To decrease the risk of damage to the motor driver during Entry,Descent and Landing, two identical motor controllers were integrated into the Drill-Control Package. Since the NC is the highest control authority in the system, it will monitor the state of the motor drivers and if any of them becomes inoperational, the NC will initiate a “hot-swap” procedure, thus ensuring that the regolith samples could be collected.

Finally, the most versatile spacecraft protection measure is through Radiation Hardened Software and defensive programming. This involves periodic self-checks and inter-system checks based on pre-established metamorphic relations. One way of achieving this is by reserving static memory on each onboard processor to store the values of WHO_AM_I registers for all other peripherals. Consequently, each slave device will transmit its own address to the master and if the received address does not match the stored constant, then the master initiates the reset procedure for that peripheral.

3.3. Payload Integration

NSS Instrument:

Operating Temp. Range (C)	Survival Temp. Range (C)	Operating Voltage Range	Power [W], Peak/Avg	Sensitivity
SM = -30 to 40 DPM = -30 to 50	SM = -40 to 60 DPM = -40 to 60	28 +/- 6 VDC	1.5/1.5	at 1eV = 80 cm^2

There are three fundamental levels of integration that have to be considered in interfacing the main instrument with the rest of the spacecraft: mechanical, electrical and software. First, the NSS is secured along all its axes to the main struts supporting the fairing structure, and enclosed by a system of springs and dampers which act as both protection mechanisms during impact and as energy storage devices for mechanical assist in driving the motors.

Secondly, the NSS was designed for compatibility with the nominal spacecraft voltage(28V), therefore no regulators or amplifiers are required for interfacing. Nevertheless, a few switching mechanisms, such as relays, have to be implemented to be able to power the instrument only when ready for operation. This is relevant not only for regulating the power consumption but also to minimise the possibility for electrical damage during descent and landing.

Finally, to interface the instrument with the data handling system a few things need to be considered: the Sensor Module(SM) embedded into the NSS outputs a voltage proportional to the thermalised electron flux emitted by the sample; the voltage is then sampled and digitalised also within the instrument by the Data Processing Module(DPM), which outputs discrete counts through an RS-422 port. Being an asynchronous protocol, the TX channel of the RS-422 can be connected to any interrupt pin of the PowerPC computer. Ultimately, within the RTOS, a thread is defined to service the interrupt and count the number of pulses transmitted to the NSS, which can then be correlated back to the electron flux of the dominant substance simply by multiplying the counts by the Sensitivity Factor(80). Both the counts and the identified elements are then transmitted to the ground station via Uplink to the LRO.

4. Payload Design and Science Experiments

4.1. Selection, Design, and Verification

4.1.1. System Overview

The payload will meet the following objective:
Determine the presence of Hydrogen on the moon at the South Pole by collecting data in Shackleton Crater and comparing its results to further support data collected by the LRO. The data collected from the WAFFLE Lander will confirm the presence of water on the moon and back of previous Scientific research that there is potential for more water on the moon.

4.1.2. SubSystem Overview

Data-Gathering Instruments (aka the Bo-Beep Suite):
The **<u>Neutron Spectrometer System</u>** is the main payload of the WAFFLE lander. It will analyze the water equivalent hydrogen abundance under the regolith. This spectrometer will contain a Sensor module and a Data Processing Module The Sensor Module contains two Helium^(3) isotope gas counter detectors, front-end electronics, and a high voltage power supply unit. The DPM receives data from the Sensor Module via an RS-422 interface.
Thermal Camera: The WAFFLE lander will use a MicroCAM 2 Low Power Thermal Imaging Core produced by Thermoteknix. The MicroCAM 2 is 43 grams and 42.5 x 50 x 25.3 mm. Operating temperature range; -40 C to 70 C. Power consumption is less than 0.6 Watts.

IR Camera: The WAFFLE lander will use the Mini-SWIR 1280JSK High Definition Camera produced by Collins Aerospace. It weighs less than or equal to 235 grams. Operating Case Temperature Range is -40C to 70C. Power Required; less than or equal to 3 watts at 20C. The MINI-SWIR camera is not space-ready. The WAFFLE team will test operations in-orbit thermal conditions and during descent and landing. A thermal vacuum chamber test will reveal whether or not copper heat straps will be necessary to thermally bond integrated circuits. Thermal pads may also be used to maintain conductivity. A hot and cold analysis should confirm space-readiness or indicate additional copper plating, thermal padding, and/or other modifications.

Impact Accelerometer: The WAFFLE lander will use a MEMS accelerometer made by STMicroelectronics. Part number LIS2DS12; a three-axis linear, high-speed, ultra-low-power acceleration sensor. The accelerometer has an integrated FIFO buffer to allow the lander to store data. A self-test capability allows for validation and verification testing. The operating temperature is between -40C and 85 C. The supply voltage ranges from 1.62 V to 1.98 V.

Power:

Provided by two 23 amp-hour lithium batteries. Shackleton Crater is permanently shadowed so the normal usage of solar panels will not be adequate. A can-sized solar panel origami unit will separate and unfold during descent of the lander. It will then orbit above the crater and beam a laser towards the lander. The lander will unfold the thin solar panels mounted to the top of the cubic body and recharge when the can-sized orbiter provides laser energy. We admit, this is a crack-head idea.

Communications: Comm package provided.

4.1.3. Precision of Instrumentation

The NSS will detect water-equivalent hydrogen to 0.5 wt% down to depths of 1 meter with an absolute accuracy of 5 to 10%. To ensure we produce the most accurate results, we will take the average of the results from the NSS instrument in that particular location, and get a better estimate for the water- equivalent hydrogen in that location. In the event that the DPM is not functioning, data from the SM will be sent directly.

4.1.4. Validation and Verification Plan

<u>NSS</u>

To increase our success rate, we are going to transmit the raw data from the sensor module and transmit the processing data from the data processing module after 30 seconds and stop taking a scan to the comm package to verify if data was actually collected. To ensure that the NSS performed as necessary, we will have a switch that will send a signal back to the command and data handling computer while the NSS is on, which will confirm that the NSS is collecting data. The switch will turn off as soon as the NSS stops collecting data, and if the data processed is sent to the command and data handling computer with actual results, then the verification of the NSS performing is complete.

Instrument Protection System
To protect the instruments onboard, specifically the NSS, we will have a small nutation damper inside the lander to maintain rotation of the body about a constant axis without perturbations. WAFFLE will utilize some relay switches to cut down the power to the NSS during EDL, to avoid electrical damage or spikes.

4.1.5. FMEA and Risk Mitigation

Risk	Likelihood	Effect on Project	Mitigation
Digital Team posing risk in lack of communication, Unrelated information/missed details, and social disconnection	Medium	Low	Clearly relay information to everyone on the team and provide written text or images that clearly relay this information.
Launch Failure	Medium	Medium	Accept
Key Employee encounters emergency/ illness	Medium	Low	Train employees before to step in and take over a role in case of emergencies. Allow for a few days spare time in case. Thorough documentation and tracing for each work package.
Loss of critical personnel.	Medium	Medium	Ensure that personnel can take over if someone leaves.
Lander or Instrument damaged during transportation or during launch	Medium	High	Secure Lander or instruments safely onboard the transportation system. Have spares parts if possible for vulnerable pieces.
Missing targeted landing zone	Medium	Medium	Recheck orbital mechanics, and ensure proper calibration of the GNC instruments.

Structural damage during landing	Medium	High	Research the material necessary to withstand the forces that it may undergo. Perform vibrational and force testing.
Instrument damaged during landing	Medium	High	Perform vibrational and force testing. Securely fasten the instrument inside the body of the lander. Additional damping mechanisms.
Instrument damaged during testing and transition between sites	Medium	High	Provide safety guidelines for handling the instruments.
Payload Incomplete/Failure	High	High	Thoroughly plan and schedule ahead to ensure delivery of the payload system. Ensure that the provider is reliable.
Lander Incomplete/Design flaw	Medium	High	Plan and Stay ahead of schedule. Redundancy and flexibility through software.

4.1.6. Performance Characteristics and Predictions

NSS

The NSS must be able to withstand the forces it undergoes during vibrational and environmental testing and be able to perform and collect data properly after all testing is complete. The instrument will be taken to the Mojave Volatiles prospector/KREX2 rover for testing, verification and validation in the field. Additional testing under thermal vacuum chamber conditions will be carried out.

4.2. Science Value

4.2.1. Science Payload Objectives

The Neutron Spectrometer System (NSS) provides a measurement of neutron fluxes consistent with > 0.5 wt% water-equivalent hydrogen (WEH) abundance buried under an amount as high as 100 cm or 1 meter depth of dry regolith when stationary for x amount of time. The NSS will be mounted on the bottom of the lander. As soon as the lander touches the surface of the moon, the NSS will begin taking measurements of the WEH below the regolith for about 3 minutes. The NSS will then take repeated 3 minute measurements until the cycle is complete. The NSS will then turn to standby mode once the cycle is complete and the Lander will move to a new location for further testing of Shackleton Crater.

4.2.2. Creativity/ Originality and Uniqueness/ Significance

Figure 4.2.2. The above three images are all snapshots of Shackleton Crater. From left to right:
(Left) A visual light image from the LROC Polar data set.
(Center) Areas of suggested water ice presence, cross referenced between Diviner, LOLA and LAMP data-sets by Shuai Li et al.
(Right) Peak temperature in the summer from a Diviner data-set (the light blue represents temperatures of around 120°K).

The most important requirement when choosing a crater as a landing/exploration site is ensuring that it allows us to complete our mission's scientific requirements. For our mission, that comes down to making sure that wherever we land, we must give ourselves the best chance of seeing ice water deposits we can get. Referencing figure 4.2.2, the eastern half of Shackleton crater is particularly water ice dense (source: Li et al. 2018 https://www.pnas.org/content/pnas/115/36/8907.full.pdf), making it a viable option as a landing site.

To further our confidence that water ice exists at our chosen landing site, we look at the peak temperatures of the crater. Water ice is most likely to exist in cold traps on the moon. This is because above freezing temperatures ice water would immediately evaporate off the surface. We found that the max temp the interior of the crater reaches is around 120°K, which is well below the melting point of water (source: Williams et al. 2019:https://www.hou.usra.edu/meetings/lpsc2019/pdf/2852.pdf)

It is also worth noting that Shackleton has a unique property which is that we predict only the eastern half of it will host ice water. This is scientifically relevant because this property can act for us like a built in control group, allowing us to analyze a crater environment that has dense ice water and one with no ice water in the same mission. This could bring us a step beyond confirming the presence of water in this particular crater, but also evaluate where this ice comes from. This could confirm the theory that ice on the moon comes from impact delivery, and therefore help us understand better where else ice-water may be.

Another reason that Shackleton is of particular scientific interest is that Shackleton crater, which has been dated as roughly 3.2–3.8 Gyr old (Zuber et al., 2012), likely predates the Cassini State transition, and is therefore one of the first lunar cold traps to come into existence (Siegler et al 2015 http://luna1.diviner.ucla.edu/~jpierre/papers/Siegler_et_al-2015.pdf). Shackleton could potentially hold a record of the oldest ice on the Moon and any volatile delivery since. "This long term stability lends credence to the apparent enhancement of hydrogen in near polar neutron spectrometer studies (Miller et al., 2014) and enhanced laser altimeter reflectance (Lucey et al., 2014), making Shackleton an especially exciting target for future study. " (Siegler et al. 2015 https://www.sciencedirect.com/science/article/abs/pii/S0019103514005120)

Our mission is unique because of its compact design, location of study and it's traversing method. In terms of its size, at less than 10kg, WAFFLE would be the smallest lunar lander to ever successfully touch down on the moon. It would also be the first mission to successfully land on a pole of the moon, and could be the first lander to confirm lunar ice water. We will also test an innovative method of transportation by using our landing thrusters to re-launch and re-land in different areas within Shackleton crater throughout our mission.

Volatile Specific Action Team(VSAT), is part of an organization tasked with bringing international cooperation on Luna. They have identified measuring the abundance of hydrogen specific volatiles in certain areas as a critical objective for research missions. (Source: LEAG Volatiles Specific Action Team Final Report 2014, https://www.lpi.usra.edu/leag/reports/vsat_report_123114x.pdf).
Through measuring the abundance of water specific volatiles within Shackleton crater, our mission will attempt to discover and characterize water ice presence, depth distribution and purity. This will inform future missions to the moon on whether the water ice deposits there can be used to sustain human life, develop rocket fuel and how easily it can be accessed, and will inform the decision to develop a lunar base. The development of a lunar base would be a major step in the exploration and inhabitation of our solar system.

4.2.3. Payload Success Criteria

The data acquired from the NSS shall be deemed successful if the payload is able to determine > 0.5 wt% WEH abundance under the regolith in Shackleton Crater. The NSS should acquire data for 3 minutes in each location during the entire mission. In addition to this requirement, the payload will be deemed a success if the payload is able to obtain, log and send back data to NASA headquarters. If we are able to collect this data at just one location, then we will deem the overall mission a success. If possible, we will try and collect data at another location through the hopping method.

4.2.4. Describe Experimental Logic, Approach, and Method of Investigation

There is a great deal of existing data available with respect to the conditions on Luna that informed decisions made in this proposal. Research from previous missions (Lee et al., 2018; https://www.pnas.org/content/pnas/115/36/8907.full.pdf; VSAT Report, 2014; https://www.lpi.usra.edu/leag/reports/vsat_report_123114x.pdf) and data from the Lunar Reconnaissance Orbiter accessed through JMARS indicate that ice water is present in the shaded polar regions of Luna. Concentrating on the South Pole, the Shackleton crater (129.783 E, -89.667 N) is the targeted landing zone for WAFFLE. Shackleton is a crater approximately 20.68 kilometers in diameter, with numerous strong ice signatures that have been detected within it in the past. The primary goal is to position the WAFFLE so it is able to land safely in the SE region of the crater, where a number of ice signatures have been detected, increasing opportunities to collect viable data. Furthermore, Shackleton is unique as it is within 1 degree of the south pole of the Moon, and will provide these opportunities with minimal risk (see 5.2.1) in order to confirm and further investigate ice signatures that have been previously detected.

The NSS instrument was selected for its ability to collect valuable data on water-equivalent hydrogen signatures down to a depth of 100 centimeters and with an error of 5 - 10%, while also minimizing the weight and size of the lander. Optimizing weight and size was an important part of being able to create a mobile lander that is capable of handling terrain and taking measurements at multiple sample locations. Additionally, the NSS is the best fit when compared to other instruments of similar cost and calibre, especially as no drill is needed to obtain samples, reducing the number of possible risks related to instrument malfunction or damage. This instrument will determine a presence or lack of water-equivalent hydrogen at a certain site before moving to the next location, therefore the collection of viable data of this nature confirming the presence or absence of water by these means will classify the mission as a success.

In addition to the NSS, there are a number of other methods of investigation that WAFFLE will employ. The science payload will also include radiation-hardened COTS instruments that will facilitate the collection of thermal data from a sensor mounted to the spinning GNC platform. These additional instruments will deliver secondary data on the thermal profile inside of the crater and the presence of water ice.

4.2.5. Describe Testing and Measurements, including variables and controls

Primary data collection and testing will be run through the NSS instrument's SM and DPM, then through the micro-computer and comm package back to NASA headquarters. As was previously mentioned, the two-part nature of the NSS prompts the need for backup, should the DPM stop functioning, in which case data from the SM will be routed through the comm package back to headquarters.

The NSS will measure water-equivalent hydrogen and thermal and IR cameras will measure the temperature profiles of the study sites as WAFFLE moves at each 3 minute interval. Thermal, altitudinal, IR, and NSS data at each study site. For all of the measurements taken, the time of measurement, position, distance from the regolith, and orientation of the SM (however topography may make this difficult), and number of iterations will be the same at each site, effectively serving as controls. The variables measured at each site will be regolith temperature and gradient, water-equivalent hydrogen content, depth of ice water, and characteristics of the ice water, all of which will be measured by the science payload. While the terrain is uncertain and factors such as dust and thermal cycling may affect sensors, the integrity and positioning of the equipment and standard of procedure will be held constant at each site. Furthermore, the camera onboard will allow observations of any irregularities in SM positioning or behavior of the lander.

Lastly, in order to account for the possible effects of lunar dust and temperature change induced expansion and contraction, a series of experiments will take place in the lab before launch in order to understand the effects of dust and temperature change on the behavior of instruments in order to calibrate the systems onboard WAFFLE.

4.2.6. Show expected data & analyses (error/accuracy, data analysis)

The systems and subsystems onboard WAFFLE will collect data on water-equivalent hydrogen content at depth (NSS), temperature profiles of the regolith (temperature camera), and IR signatures and images (IR camera).

NSS data will be collected by the SM module and processed by the DPM, which digitizes the signals from the SM and measures pulse height and count rate before transfer through the micro-computer and transmission of results back to the LRO and downlink to NASA headquarters. Raw signals and data from the SM will also be sent directly back through the micro-computer and comm system in the event of DPM failure or malfunction. Temperature and IR data and images will be processed by the micro-computer and transmitted using the comm system. The use of thermal and IR will also allow for backup data in the event that lunar dust affects the shorter wave IR imaging data. Raw data from all instruments will be sent in order to assess accuracy of processing and preserve any data in the event of data processing-associated problems on WAFFLE.

Using pre-launch testing and error calculation and calibration tests, data will be processed accordingly and any calculations made or results used will include appropriate error propagation for all data collected as applicable. Data from the GNC and impact accelerometer will also be transmitted in the event of a landing issue or malfunction in order to properly assess the problem and advise future missions.

Expected images from the MicroCAM 2 Low Power Thermal Imaging Core produced by Thermoteknix should track closely to the image below (*Figure 4.2.6. a.*).

Expected data collected and processed by the NSS instrument should reflect differences in water content as was demonstrated clearly by Elphic et al. (2015); (*Figure 4.2.6. b.*).

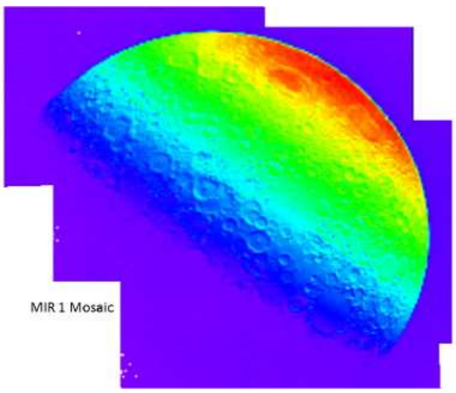


Figure 4.2.6. a. Photo Credit: NASA Ames Research Center. The above image shows a mosaic of images from the far-side of the moon taken by the LCROSS MIRICLE thermal imaging camera built by Thermoteknix.

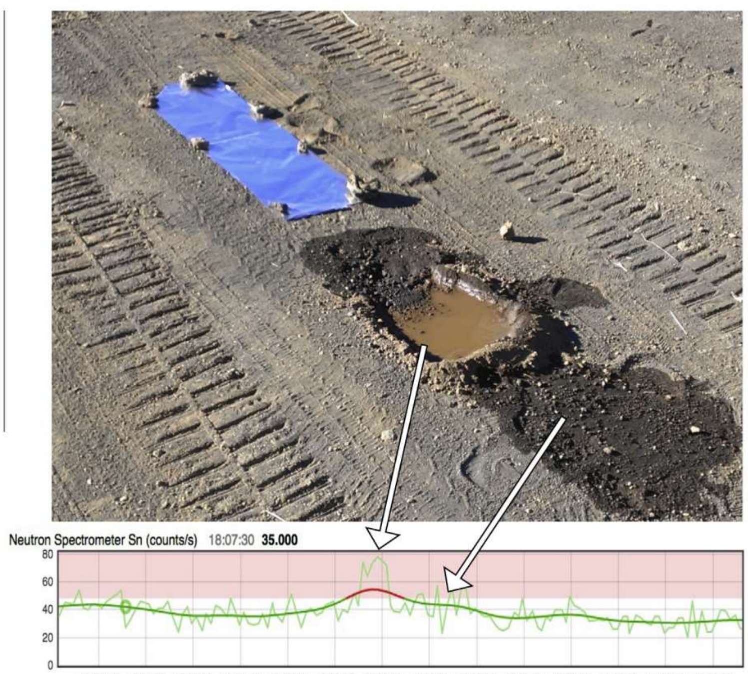


Figure 4.2.6. b. NSS output data and associated terrain from fig. 7 Elphic et al. (2015): Simulated real-time lunar volatiles prospecting with a rover-borne neutron spectrometer in *Advances in Space Research* vol. 55, pp. 2438-2450.

5. Safety and Environment

5.1. Personnel Safety

5.1.1. Safety Officer

Dylan Tabalan was assigned safety officer and is responsible for identifying and mitigating any possible hazard that can endanger the safety of personnel throughout the mission. Research in team safety includes NASA's Office of Safety and Mission Assurance (OSMA) and Occupational Safety and Health Administration (OSHA).

5.1.2 List of Personnel Hazards

After further research, the list of personnel hazards includes:

- Assembly/Testing hazards
- Electrical hazards
- Explosive and pyrotechnics hazards
- Handling of batteries
- Machining/Manufacturing hazards
- Spread of illness/disease

5.1.3 Personnel Hazard Mitigation

- Make sure assembly and testing are done in a safe environment and controlled environment with proper notification to all personnel
    - Make sure to read Material Data Sheets
- Work on electrical components with precaution and never while the circuit has a live current
    - Notify any and all personnel when adjusting electrical components to avoid accidents
- Handle possible explosive and pyrotechnic materials with extreme care and with proper PPE
    - Keep proper fire protection equipment on site for emergencies
    - Practice proper evacuation protocols for fire hazards
- Make sure to check safety data sheets and handle batteries with care and as directed
    - Never use a damaged battery as it may explode
- Make sure proper personal protective equipment (PPE) and clothing attire is worn when manufacturing or machining

- ❖ Abide by Centers for Disease Control's protocol in the event of a pandemic and provide adequate sick leave days and support for personnel

5.2. Lander and Payload Safety

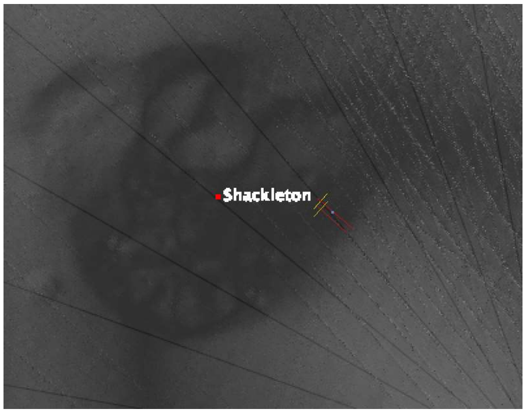
5.2.1 Environmental Hazards

While Shackleton crater provides a large landing zone, it is not free of environmental hazards. The accuracy of the lander will likely be within a 100 meter radius, therefore the terrain must be accounted for within the target LZ and throughout the entire crater.

- ❖ Crater topography: elevation and slope transects taken around the crater indicate slopes up to 32 to 46 degrees about the S, SW, and W rims and a ~1,250 m drop to the bottom of the crater, slopes up to 21 to 40 degrees in the NW and N with drops up to 1,500 m, and slopes nearing 32 degrees to the NE and E, with drops of up to 1,750 m to the bottom of the crater basin.
- ❖ Landing safely: while a safe LZ has been chosen to avoid risks associated with crater topography, aiming the lander at such a precise LZ poses an engineering challenge. Because of this, it is quite possible that the lander could fall, tip, flip, get stuck, or get damaged in some way due to topography and terrain. In the event that this happens, the environment could directly hinder or prohibit the collection of viable data should it land somewhere from which it cannot maneuver safely.
- ❖ Lunar dust and debris: could interfere with WAFFLE's ability to use its cameras and the NSS instrument for observation and data collection.
- ❖ Dramatic temperature changes: would cause expansion and contraction with thermal cycling. The longevity of this mission may make this somewhat negligible, but observing its effects could be both problematic for the instruments and structural components, but also useful as it would provide information about the effects of thermal cycling on equipment (Williams et al., 2019; https://doi.org/10.1029/2019JE006028)

=5.2.2 Environmental Hazard Mitigation

Choosing a safe target LZ was the best way to avoid environmental hazards associated with crater topography.



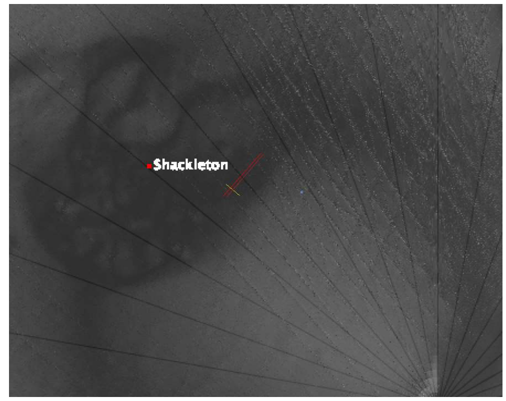


Figure 5.2.2. Perpendicular transects across the target LZ of Shackleton crater measuring slope and change in elevation. This particular location is ideal for landing in an area with previously detected ice signatures in as low-risk of a manner as possible (Images from JMARS).

- ❖ Target area: previous studies have located regions within the crater likely to contain ice, therefore the target LZ lies in the SE portion of the crater basin. Located near the striations that can in the satellite image (fig. 3), transects mark an area with gradual slopes up to 22 degrees and drops of 10 m in some places. Surrounding areas are characterized by sudden drops up to 30 m.
- ❖ Safe LZ: Smaller cross sections (fig. 3) reveal areas approximately 0.1 km in diameter with elevation changes as small as 5 m and slopes dropping under 4 degrees. Furthermore, a soft landing will provide more protection for the instruments and structural integrity of the lander on any terrain.
- ❖ Dust and debris protection: Cover/shield to protect NSS instrument sensor module from lunar dust between measurements and during movement between sites.
- ❖ Thermal protection for instruments and lander

6. Activity Plan

6.1. Budget

Year	Yr 1 Total	Yr 2 Total	Yr 3 Total	Yr 4 Total	Yr 5 Total	Yr 6 Total	Cumulative Total
PERSONNEL	10	10	10	10	10		
Total Salaries	$ 800,000.00	$ 800,000.00	$ 800,000.00	$ 800,000.00	$ 800,000.00	$ -	$ 4,000,000.00
Total ERE	$ -	$ 223,280.00	$ 223,280.00	$ 223,280.00	$ 223,280.00	$ -	$ 893,120.00
TOTAL PERSONNEL	$ 800,000.00	$ 1,023,280.00	$ 1,023,280.00	$ 1,023,280.00	$ 1,023,280.00	$ -	$ 4,893,120.00
OTHER DIRECT COSTS							
Total Materials and Supplies	$ 200,000.00	$ 75,000.00	$ 20,000.00	$ -	$ -	$ -	$ 295,000.00
Publications	$ -	$ -	$ -	$ -	$ 5,000.00	$ -	$ 5,000.00
Total Travel	$ -	$ -	$ 14,355.00	$ -	$ -	$ -	$ 14,355.00
Total Services	$ 7,500,000.00	$ 2,000,000.00	$ -	$ -	$ -	$ -	$ 9,500,000.00
Total Equipment	$ 1,250,000.00	$ 500,000.00	$ -	$ -	$ -	$ -	$ 1,750,000.00
Instrumentation (NSS)	$ 3,500,000.00						$ 3,500,000.00
Total Subcontracts	$ 2,000,000.00	$ -	$ -	$ -	$ -	$ -	$ 2,000,000.00
Total Participant Support	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Tuition Remission (not applicable)	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Total Direct Costs	$ 15,250,000.00	$ 3,598,280.00	$ 1,057,635.00	$ 1,023,280.00	$ 1,028,280.00	$ -	$ 21,957,475.00
Total MTDC	$ 8,500,000.00	$ 3,098,280.00	$ 1,057,635.00	$ 1,023,280.00	$ 1,028,280.00	$ -	$ 14,707,475.00
Total Subcontract F&A	$ 200,000.00	$ -	$ -	$ -	$ -	$ -	$ 200,000.00
College or University F&A	$ 850,000.00	$ 309,828.00	$ 105,763.50	$ 102,328.00	$ 102,828.00	$ -	$ 1,470,747.50
Total F&A	$ 1,050,000.00	$ 309,828.00	$ 105,763.50	$ 102,328.00	$ 102,828.00	$ -	$ 1,670,747.50
Total Manufacturing Margin (~50%)	$ 3,750,000.00	$ 1,000,000.00	$ -	$ -	$ -	$ -	$ 4,750,000.00
Total F&A Margin (~10%)	$ 105,000.00	$ 30,982.80	$ 10,576.35	$ 10,232.80	$ 10,282.80	$ -	$ 167,074.75
Total General Margin (~30%)	$ 4,575,000.00	$ 1,079,484.00	$ 317,290.50	$ 306,984.00	$ 308,484.00	$ -	$ 6,587,242.50
Total Margins Cost	$ 8,430,000.00	$ 2,110,466.80	$ 327,866.85	$ 317,216.80	$ 318,766.80	$ -	$ 11,504,317.25
Total Project Cost	$ 16,300,000.00	$ 3,908,108.00	$ 1,163,398.50	$ 1,125,608.00	$ 1,131,108.00	$ -	$ 23,628,222.50
FED FLOW THROUGH (JPL, ARC, etc.)	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Total Project Cost	$ 24,730,000.00	$ 6,018,574.80	$ 1,491,265.35	$ 1,442,824.80	$ 1,131,108.00	$ -	$ 34,813,772.95
F&A %	10%	10%	10%	10%	10%	10%	
	Budget						
ERE Staff		0.28	0.28	0.28	0.28	0.28	

Our total budget margin is $186,227.05. This is a smaller margin than we would like. To manage budget, careful fund allocation to the development of the NSS instrument will be critical. The price of the engineering model copy is $500k, but the current estimate to develop a flight version for a NASA mission is $3.5M. This is one of the places in our budget plan that we have the opportunity to minimize costs by being financially efficient.

6.2. Schedule

As shown in section 1 of the PDR, the majority of tasks will take place in the span of 1 year where the PDR and Phase B is complete by the month of May. The schedule has shifted dates for the PDR being due in May instead of April due to COVID-19.

In the table below, you will see a timeline of the schedule starting at the mission end or Phase F, and moving backwards with the phases highlighted in darker blue, and all other tasks in lighter blue.

Table 1: Project Schedule/Timeline

Month	Date	Year	Task
October	27	2021	Phase F: Closeout Due
October	27	2021	Mission end
October	20	2021	Phase E: Operations and Sustainment Due
October	20	2021	End Science Operations
October	18	2021	Perform Science Operations
October	18	2021	Land in Shackleton Crater
October	17	2021	Phase D: System Assembly, Integration and test, Launch and checkout Due
October	17	2021	Launch
September	12	2021	SMSR
March	30	2021	CDR
January	20	2021	Phase C: Final Design and Fabrication Due
January	18	2021	SIR
May	17	2020	Phase B: Preliminary Design and technology Due
May	17	2020	PDR DUE
February	3	2020	Phase A: Concept and Technology Development Due
February	2	2020	MCR
February	2	2020	Concept Design

January	14	2020	Project Start

6.3. Outreach Summary

Outreach will be conducted via social media, press releases, community outreach, and via scientific journals.

Social Media

1. Update posts on Social Media using the handle @waffleteam.
2. Q&A via social media platforms.

Press Release

1. Press Releases will be made to the general public on a national and community-level.

Community

1. Team members will contact local colleges/K-12 schools to set-up and participate in live Q&As.
2. Victor Covasan will advise a team of students from his high-school who are competing for NASA' MoonCamp, especially from the point of view of exploiting ISRU and the future stages; storing the purified water, maintaining rovers and the other robots, radiation protection, thermal insulation, etc..

Peer-Review

1. Publish findings in scientific journals.

6.4. Project Management Approach

WAFFLE is a team based on the West Coast, United States.
Organization and Primary Responsibilities: WAFFLE encompasses two sub-groups; the Engineering team and the Science team. The Science Team's responsibilities included performing the first-half of the research involving the various science instruments (science payload), landing location and scientific evidence to support the team decisions. The Science Team later provided this information to the Engineering team to enable the Engineering aspect of the Mission Concept.
Team Structure: WAFFLE split into tiger teams to address and solve critical issues and to complete sections of the PDR. The tiger teams met at specified intervals of time to collaborate and update other teams on the status of the deliverables. Although we had official and unofficial "team leads", in general, the team was largely self-motivated and led themselves.
Issues: Due to the unforeseen coronavirus pandemic, the team had to slightly modify operations to accommodate new locations and schedules. The team also worked to accommodate new final schedules, family-related incidents and extraneous circumstances. The tiger teams picked up the slack and filled in for other tiger teams when it was necessary.

Preliminary Actions: Upon team formation, Work breakdown structure was drawn to separate key areas and main work packages between the team members. Deputy engineers and scientists were appointed as an interface between the technical subteams and the management.
Preliminary Communication: The team used a Kanban board(Trello) as the main means for progress tracking, as it allowed for deadlines to be set, link attachments to the location of specific work packages on Google Drive or GitHub. The team also made use of a communication platform called Discord. It was the primary method of messaging between team members and allowed for easy scheduling of meetings, voice calls, video calls, and distribution of information.
Development Process: Although the development process followed a path close to the Waterfall model, with the engineering design only properly starting after the science objectives were established, in a future design iteration it would be desirable to adopt a concurrent approach to mission design.

7. Conclusion

Through research and project development, the driving goal of collecting data to help inform future missions and learn more about the Moon stayed constant. The data that the NSS and subsystem instruments will collect is part of a much bigger picture involving human habitation on the moon and more adventurous exploration of space, answering a great number of questions.

Working within a specific budget, size and weight constraint, and time frame has yielded a superior product that will perform important scientific work as efficiently as possible if landing and testing procedures occur successfully.

Not only will this data inform future missions, but it will serve to validate previously collected data from other missions, sensors, and satellites in orbit. If WAFFLE can confirm previously collected water ice signatures from the surface, other similar observations and measurements will also be validated, allowing more research relying on water ice detection in the future.

Overall, WAFFLE’s journey will document a unique mission using state-of-the-art equipment and be a small, but vitally important part in paving the way for future human activity on the moon.