1. Introduction and Summary
1.1. Team Introduction

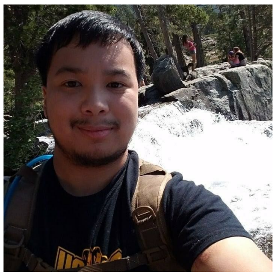
The team consists of various talented students:

Marcos Figueroa
Member of Landing Site and Transponder Teams
Marcos is a senior at the California State University, Bakersfield studying physics. He brings his expertise in physics to the team. He hopes to obtain his masters in engineering or physics and to be a part of a team that works on engineering projects related to aerospace.

Madeleine Graham
Project Manager; Leader of Logistics Team; Member of Scheduling and Landing Concept Teams
Madeleine is a second year student at the College of San Mateo, San Mateo (CA) studying physics and engineering. She brings her expertise in project planning and management. She hopes to someday work in Mission Control for the International Space Station or Gateway.

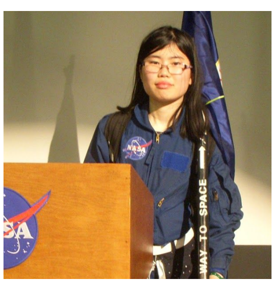
Kim Huynh
Deputy Project Manager; Member of Scheduling Team
Kim is a sophomore at the University of Idaho, Moscow (ID) studying computer engineering. She brings her expertise in coding to the team. She hopes to someday work in the aerospace field.

Jacob Rogers
Member of Research and Landing Site Teams
Jacob is a freshman at Whatcom Community College, Bellingham (WA) studying electrical engineering. He brings his expertise in CAD and research to the team. He hopes to someday transfer to a four year university to study electrical engineering and work on rovers for NASA.



Max Tchen
Leader of Engineering Team, Member of Manufacturing and Landing Concept Teams
Max is a fourth year student at California State University, Northridge studying Mechanical Engineering. He brings his expertise in CAD and Finite Element Analysis and Manufacturing to the team. He hopes to someday build products that benefit society.

Paulina Umansky
Leader of Science Team; Member of Research, Landing Site, Landing Concept, and Documentation Teams
Paulina is a first year at the University of California, Berkeley studying physics and planetary science. She brings her expertise in project organization and CAD to the team. She hopes to someday design sustainable technology and missions to other planets.



Wendy Yang
Member of Engineering, Transponder, and Documentation Teams
Wendy is a third year at the University of California, Berkeley studying mechanical engineering and political science. She brings her expertise in Solidworks and MATLAB to the team. She hopes to someday work on space policy in Washington, D.C.

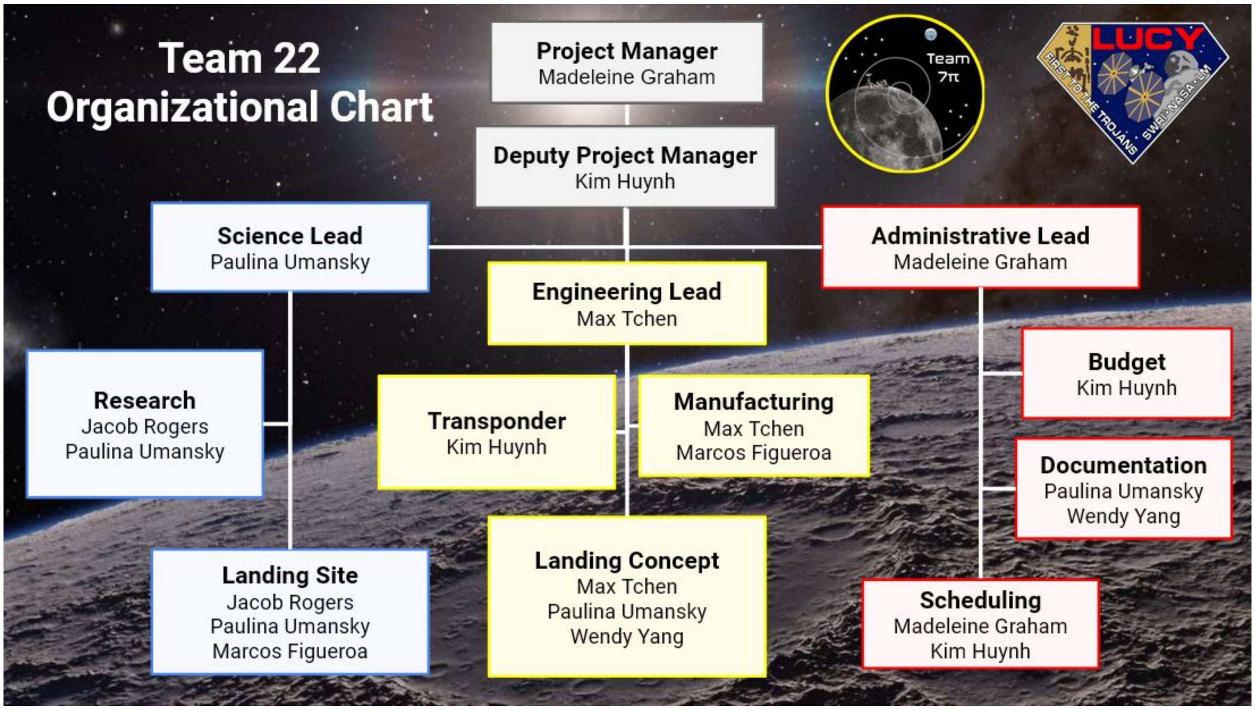


Figure 1. The Organization Chart of Team 7π

1.2. Mission Overview

1.2.1. Mission Statement

The goal of the lunar lander, PIE-L (Preliminary Ice Exploration Lander), is to characterize water within Shackleton Crater. The mission's science objectives are to:

1) **Verify the existence of water.**
2) **Collect data on the depth and distribution of water.**
3) **Collect data on the elemental distribution of the crater floor.**

The verification of the existence of water on the moon can contribute to humanity's understanding of the moon itself and of its potential as a gateway to the outer planets. Data on the amount and distribution of water ice, as well as its proximity to other elements, can inform future manned missions to the moon by providing guidance on how much water ice is available for use as a resource and where this resource can be found. Water ice reserves on the moon could be used for human consumption, rocket and rover fuel, and as a protective barrier against some forms of space radiation. Therefore, lunar water existence verification, data on depth and distribution of lunar water, and data on lunar water's proximity to other elements is vital for humanity to continue its journey to the stars.

1.2.2. Mission Requirements

Team 7 Pi's Lunar Lander, PIE-L (Preliminary Ice Exploration Lander), will launch from a lunar orbiter and make a controlled landing within the vicinity of its designated landing site of Shackleton Crater. After landing, it will start to use a smaller version of DAN (Dynamic Albedo of Neutrons) to measure the presence of H and OH molecules. PIE-L will deploy its robotic arm, pressing its sensors to the surrounding surface, and it will use APXS (Alpha particle X-ray Spectrometer) to detect the presence of other elements and TECP (Thermal and Electrical Conductivity Probe) to measure soil thermal conductivity and humidity.

PIE-L will be equipped with a transponder to relay communications about its instrument findings back to Earth.

PIE-L will be built to the following specifications: It will be no larger than a 60 cm cube and have a mass of no more than 10 kg. Mission costs are capped at $35 million.

PIE-L shall be manufactured and tested on time to make its launch window in October of 2021.

1.2.3. Mission Success Criteria

The following criteria describe baseline success for PIE-L in chronological order. For the bare minimum, each of these criteria must be met:

- PIE-L is within no greater than 10% of its proposed budget of $35 million
- PIE-L is manufactured in time for launch
- PIE-L accomplishes a controlled landing from its orbit without severe damage to its instruments.
- PIE-L lands within Shackleton Crater.
- Communication from the transponder with the mission team begins after landing on the moon and within PIE-L's life-cycle.
- At least one instrument successfully reads data from the surface of the moon and is able to communicate it back to Earth.
- Data is archived and able to be accessed by the public after its mission is over.

The following criteria describes the best case scenario for a very successful mission:

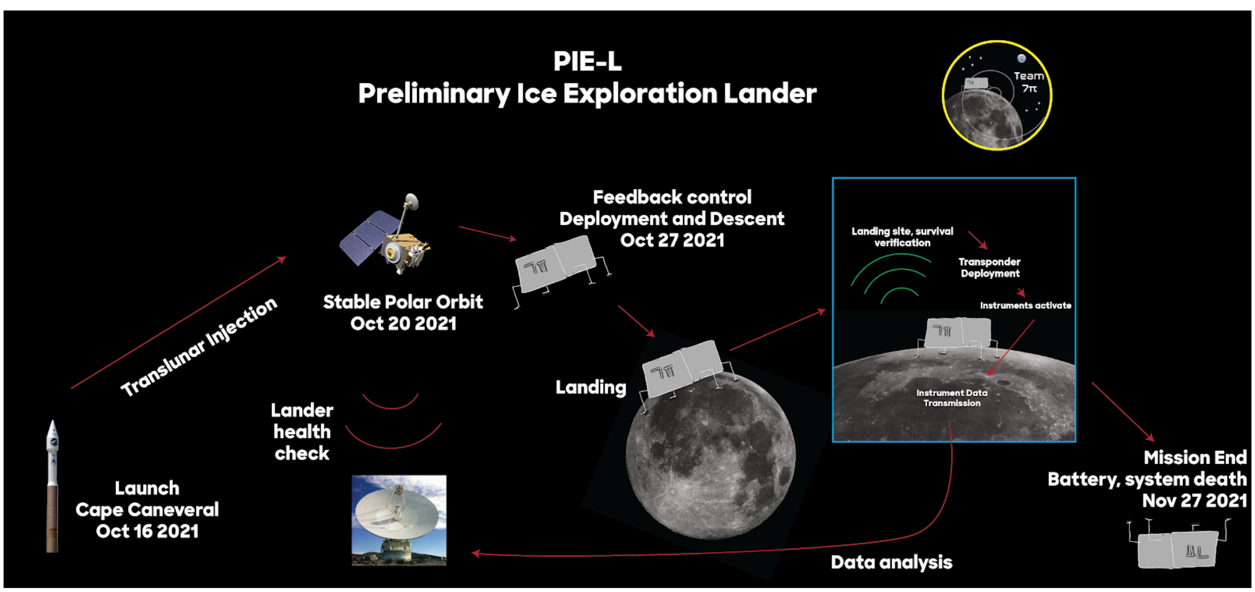
- PIE-L is within no greater than 5% over its proposed budget of $35 million
- PIE-L lands within 20 meters of its designated landing site.
- PIE-L accomplishes its landing with little to no damage to any of its instruments
- Communication from PIE-L's transponder is prompt and elucidating to PIE-L's current situation up until its life-cycle ends

- All three of PIE-L's instruments read as much data as there is available within reach of its robotic arm.
- Instrument data is able to answer all scientific questions about the presence of water in the craters on the moon's poles and other conditions of the moon's surface. These scientific questions include: Is there detectable water ice on the moon (that can be detected via lander, not just via satellite)? What is the depth and distribution of water in Shackleton? What kinds of elements (apart from H and O) are present near water ice deposits, and is there any correlation between nearby elements and increased water content?
- Data is archived and utilized greatly within the scientific and STEM educational community.

The following criteria define mission failure. If any one of the following happens, the mission is a probable failure:

- PIE-L goes over 10% of its proposed budget during development.
- PIE-L is not ready for launch in time for its proposed window
- PIE-L does not successfully launch from its orbiter.
- PIE-L is damaged heavily so that its instruments do not work.
- PIE-L's scientific instruments may work, but its transponder does not work.
- PIE-L's instruments return data, but the data is too vague to interpret.
- Data is not archived or shared.

1.2.4. Concept of Operations (Graphic)



Launch Phase

Our launch window is planned for the week of Oct 16, 2021. The orbiter will enter stable lunar orbit four days later.

Orbit Phase

PIE-L is onboard the orbiter that will be around the moon's poles. During this time, the orbiter will perform its primary mission. The team will confirm the status of the lander and confirm a trajectory that will place PIE-L in the desired location in order to start its descent phase. This stable orbit phase will last one week.

Descent Phase

Once a stable orbit is confirmed, PIE-L will exit the orbiter and begin its descent into Shackleton Crater. After PIE-L's transponder verifies successful landing has occurred, the communication package will deploy and begin lunar scientific objectives. The mission objectives of collecting data with PIE-L's instruments and transmitting the data to Earth will be accomplished within a month of landing.

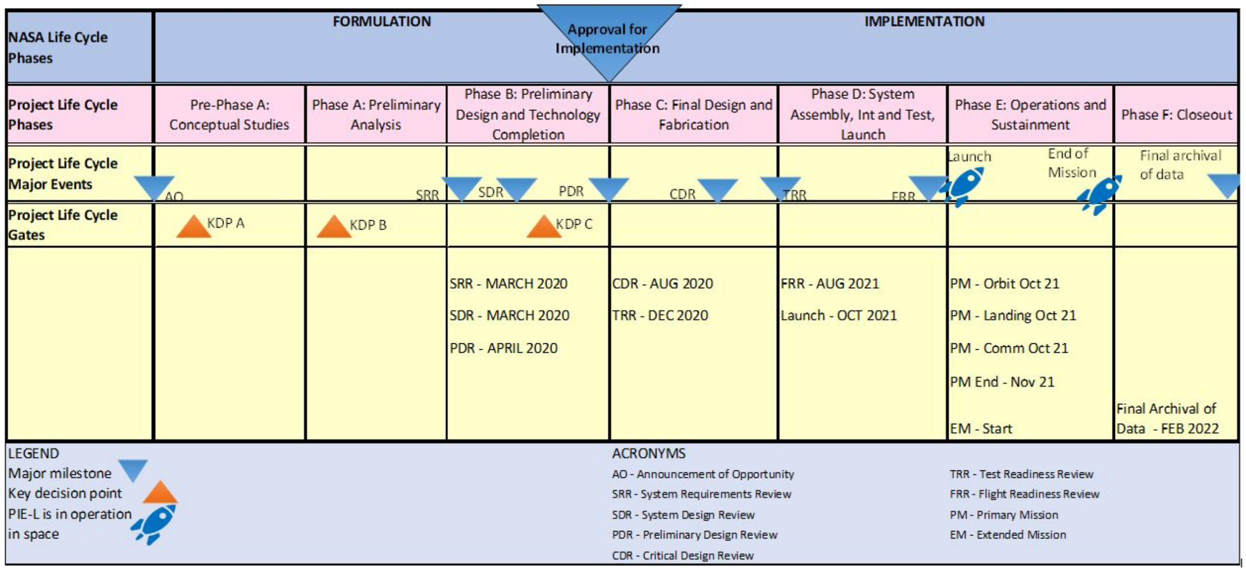
Information Analysis Phase

The team will analyse the transponded data from PIE-L's three instruments on whether the data collected confirms presence of water in the crater. The team will also analyse data on the depth and distribution of H and OH-bearing molecules, and collect data on the elemental distribution within Shackleton Crater in order to characterize the presence of any past or present existence of water molecules. This analysis phase will occur in November 2021.

Information Archival Phase

The team will then archive and store the data in an easily accessible manner. The team's outreach officer will make sure to publicize data in terms easily understandable and relatable to the average person. The overall mission will end February, 2022.

1.2.5. Major Milestones Schedule

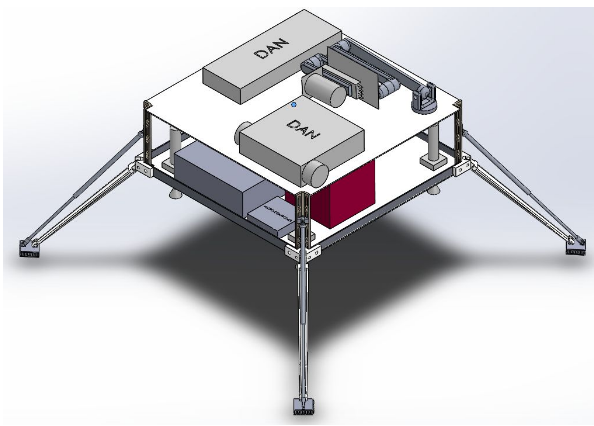


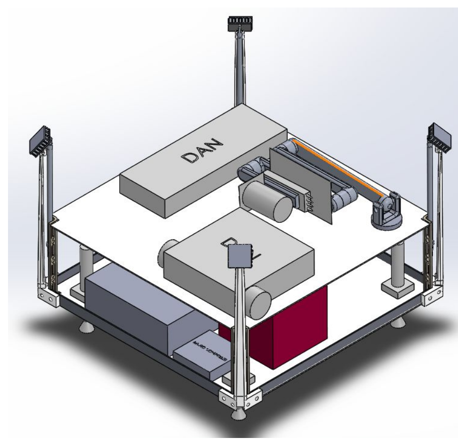
Above is a graphic of PIE-L's major milestones. KDP A refers to the decision on science mission goals about what aspect of the concept of water being present on the lunar surface the team is going to focus on studying. KDP B refers to the decision about where PIE-L is going to land. KDP C refers to the science team's decision on what instruments to include on PIE-L.

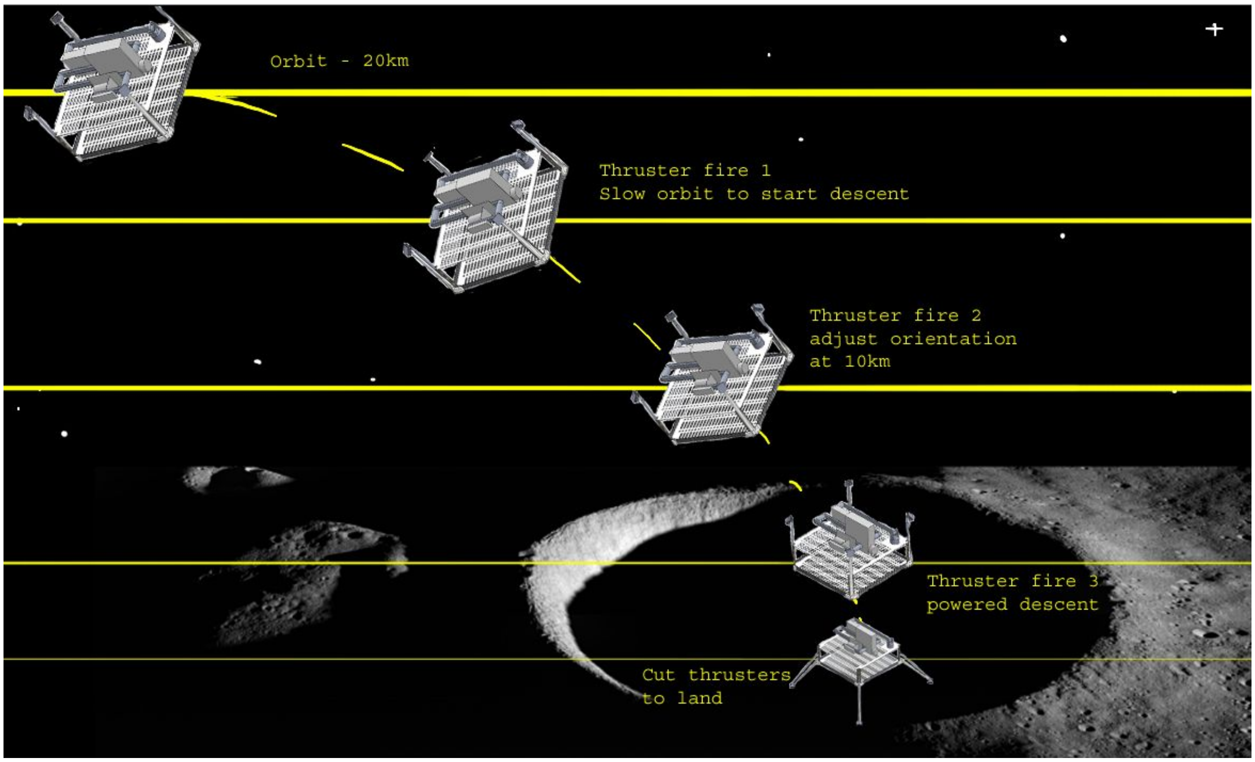
Pending approval of this PDR, Team 7pi will start work on the CDR for PIE-L, which we will estimate to be finished in August 2020 with a margin of about a month. The CDR will be more specific about materials and manufacturing as well as include more definite descent calculations and firmer estimations on cost. The TRR is expected to be finished around December of 2020 with a month of margin. Testing will be one of the longest phases, ending with the finishing of the FRR in August of 2021. There will be a margin of two months. PIE-L will Launch in October of 2021 and data collection will commence. Its mission will end in November 2021. Data archival will finish February of 2022.

1.3 Descent and Lander Summary

The lander is designed around a box frame with an open top. Four legs are mounted at each 90 degree corner of the lander that deploy prior to landing through the use of telescoping tubes. The legs will be operated with a gas cartridge that will fill the telescoping tubes thus extending them. Each leg will be able to move independently as the landing site will perhaps not be on flat terrain. To prevent the legs from being forced to extend even when touching the lunar surface a strain gauge will be mounted at the feet to set a limit in deflection to limit the gas released. The overall structure of the vehicle when stored will be 15068.07 cubic centimeters. The leftover space would be used to mount fuel for the descent control thrusters, Centaur computer, communications, circuitry and the battery source. The lander’s structure weighs 15.75kg. The payload weighs 2.91kg. In its entirety, the lander weighs 2.69kg which is less than the allotment of 10kg.







(*Islands in the Dark | Lunar Reconnaissance Orbiter Camera*, n.d.)

PIE-L will perform a powered descent onto the lunar surface from orbit.

PIE-L will leave its orbit at 20km above the surface of the moon and decelerate. The team decided to opt for a powered landing rather than a ballistic landing, and so the entry angle will be shallow. The descent system is made up of four thrusters on each side of the lander and has two functions - one is to control the orientation of the lander as it makes its final descent. The second function is to provide the necessary force to bring the lander's speed down to 0 m/s. The first system will be used to exit the orbit and perform an orientation adjustment at 10km. The second system will be used to perform a slow descent. The slow descent will start close to the surface within Shackleton Crater and the lander will slow to 0 m/s. At around 7.69m, the lander's thrusters will turn off and the lander will "float" down, reaching a landing velocity of around 5 m/s.

1.4. Payload and Science Summary

Science Payload Overview

The science payload contains three instruments: the Thermal and Electrical Conductivity Probe (TECP), the Dynamic Albedo of Neutrons (DAN), and the Alpha particle X-Ray Spectrometer (AXPS), which, respectively, fulfill the science objectives #1, #2, and #3.

TECP is an instrument that can confirm the existence of water ice in regolith or rock through measurements of dielectric permittivity (capacity of holding an electrical charge), electrical conductivity, temperature, thermal conductivity, volumetric heat capacity, and relative humidity, fulfilling science objective #1(Zent et al., 2009). It collects data via 1.5cm needle-like probes that are inserted into the ground(Zent et al., 2009). The whole device has a volume of 80.311 cubic centimeters(Zent et al., 2009). According to Dr. Michael Hecht, who was the project lead for the Microscopy, Electrochemistry, and Conductivity Analyzer (MECA) instrument suite which includes the TECP, the TECP weighs under .1 kg (*Phoenix Mars Mission - Mission - Teams - Michael Hecht*, n.d.-a).

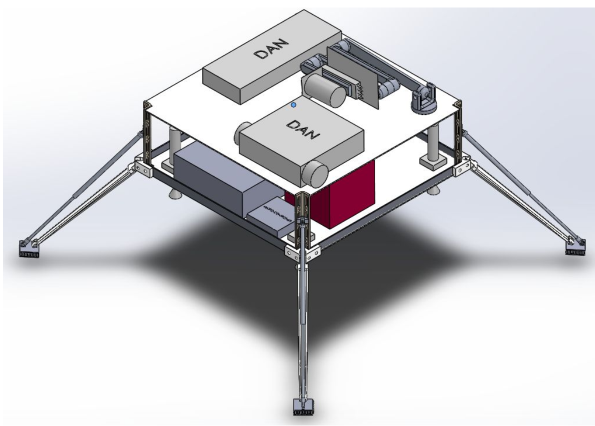
DAN is a two-piece instrument that examines the depth and distribution of water beneath the surface of the lander, fulfilling science objective #2(NASA/JPL-Caltech, n.d.). One piece of the device is the Pulse Neutron Generator, which pulses high-energy neutrons into the ground, while the other is the Detectors and Electronics, which detects changes in the reflected neutron beam to detect subsurface Hydrogen(NASA/JPL-Caltech, n.d.). The pair has a total volume of 4539.378 cm^3, and a total mass of 4.7kg(Litvak et al., 2008). It is placed near the base of the robotic arm, allowing it to scan a greater area when the arm moves than it would if it were on the stationary part of the lander.

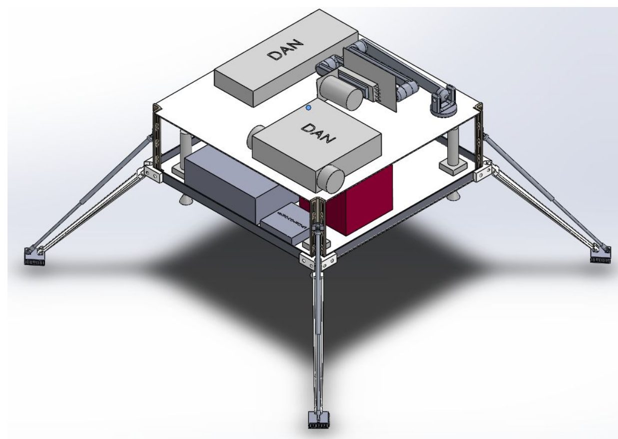
APXS is an instrument that determines the elemental composition of regolith and rocks, fulfilling science objective #3(*APXS Instrument Information – MSL – Mars Science Laboratory*, n.d.-a). It is .25kg and 189.94 cubic centimeters in volume (it is a cylinder with a 5.3cm diameter and 8.4cm height, with a 6.8cm thin square plate on the end — for calculation, thickness of the plate is assumed to be .1cm) while its accompanying electronics are .12kg and 170 cubic centimeters in volume (17cm x 10cm x 1 cm)(Rieder et al., 2003). It can detect most chemical elements on the surface that it examines except for Hydrogen(*Mars Pathfinder Instrument Descriptions*, n.d.-a). It makes observations of how much of each kind of element is present by scanning rocks and soil that are in contact with the instrument(Gellert, n.d.-a).

Significance of Payload

The payload is significant to both the science and space exploration communities. Given that there have been only two soft landings on the moon since 1974(Devlin & Lyons, 2019), a detailed in-situ analysis of the moon's water ice reserves is not only long overdue, but is also necessary for major scientific advances in fields such as lunar formation and composition. To enable humanity to understand our universe beyond the moon, these details on the depth, distribution, and proximity to other elements of lunar water ice, not to mention indisputable confirmation of the existence of lunar water ice, will allow future space exploration missions to find and utilize lunar water resources.

PIE-L will make use of a robotic arm in order to place its scientific instruments where they need to be to effectively collect data. TECP needs to be inserted into the ground in order to collect data and APXS needs to be placed on soil and rocks in order to collect data. TECP, APXS, and DAN are all three on the robotic arm that can swivel and access more than one sample location.



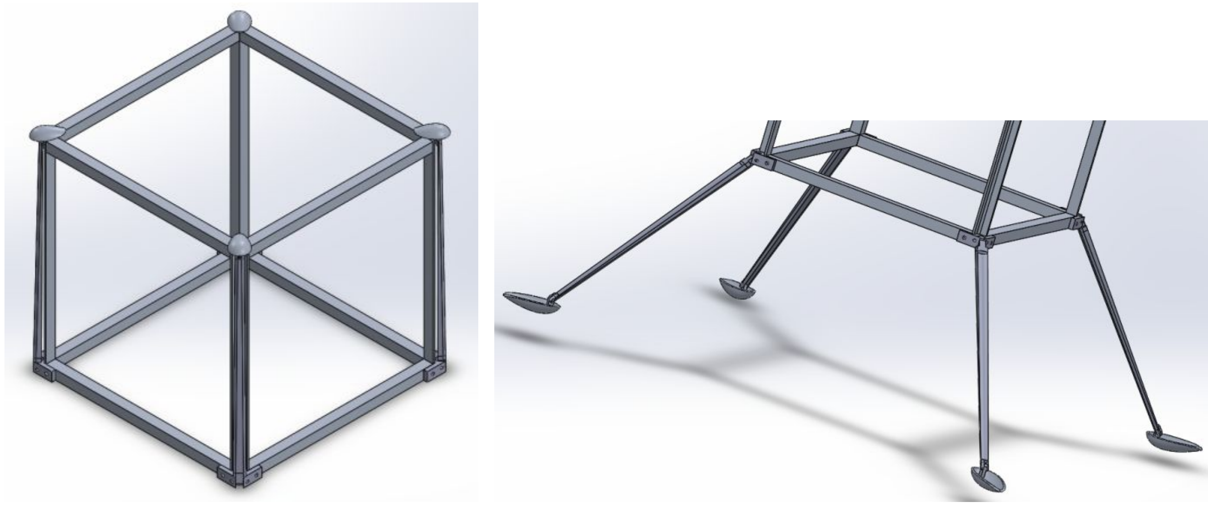


2. Evolution of Project

2.1. Evolution of Descent and Lander

Descent

Iteration 1



Above: Lander in closed position (left) and in open position (right).

Iteration 1 Lander Description

The first design of the lander is a cube with feet because the team desired to provide structural support and protection for the payload to fit inside. The first iteration of the lander is made out of aluminum 6061 T6 and has a mass of 6.7 kg. It has foldable legs so it can fit into the volume constraint of a 60cm cube. Initially the team considered using a composite such as carbon fiber instead of aluminum, but Carbon fiber is weak under compression, but strong under tension, and epoxy is vice versa, a carbon fiber frame for the spacecraft would have to be treated by epoxy to be structurally sound. This adds complexity, cost, and time to the manufacturing process. This first iteration of the lander was not used because the team considered more than half of the allocated mass of 10kg to be too heavy and did not have a fully developed descent system.

Iteration 1 Descent Description

In this first iteration of the powered descent plan, at the final stage of landing the lander would cut engines and drop the last 3m on its crushable aluminum feet. The crushable feet will allow for simplification of the lander as well as dissipate the landing impact. The first iteration of the descent is not yet fully developed to ensure a safe landing, so it was not used.

Iteration 2

Above: Revised lander with improved structural support (left); removed top (middle); and advanced compressed-gas landing system (right).

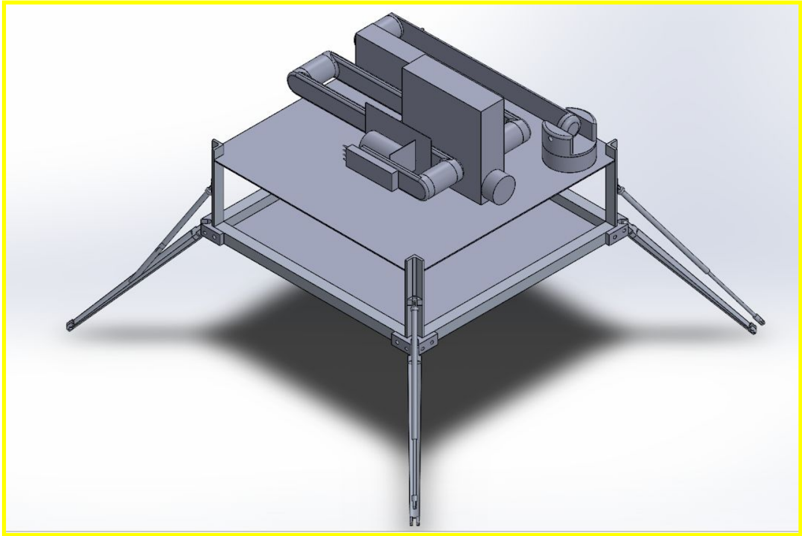
Iteration 2 Lander Description

After reviewing Iteration 1, the Landing Concept Team decided to improve structural support on the lander's legs to improve reliability, therefore improving our landing system. Since the structure of the lander was previously a majority of the payload's allocated mass (6.7kg/10kg), the team decided to reduce the lander's mass by removing the top part of the cube, allowing iteration 2 to be less massive. And, the team decided to use a compressed gas landing system that deploys legs for a successful soft landing. The landing concept so far is missing a retro propulsion system that will allow it to land, so the team is conducting R&D in that department for iteration 3. Though this iteration improved upon the landing system, it is not being used because the descent system needs to be more developed (e.g. include thrusters, engines, a fuel tank, etc.)

Iteration 2 Descent Description

Although the lander design changed, the descent did not. This iteration also did not yet have thrusters and accompanying features to match our descent plan, as the team had been still conducting research into the specifics of landing systems at this point.

Iteration 3:



Above: Revised lander with platform on top to support robotic arm for instruments; space inside for power source and transmitter.

Iteration 3 Lander Description

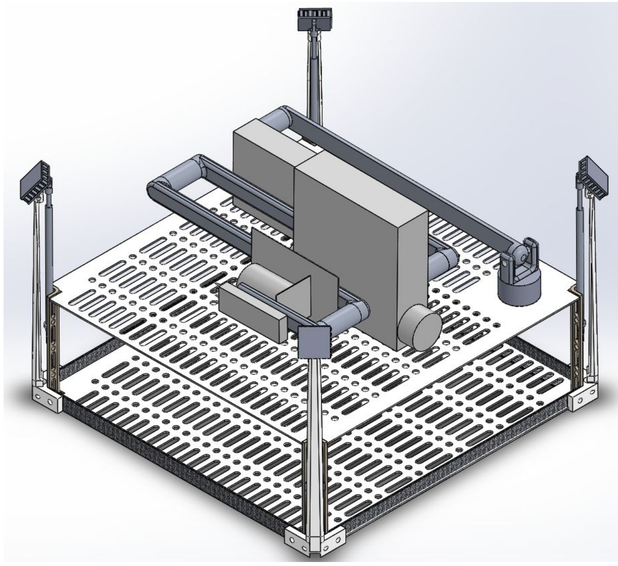
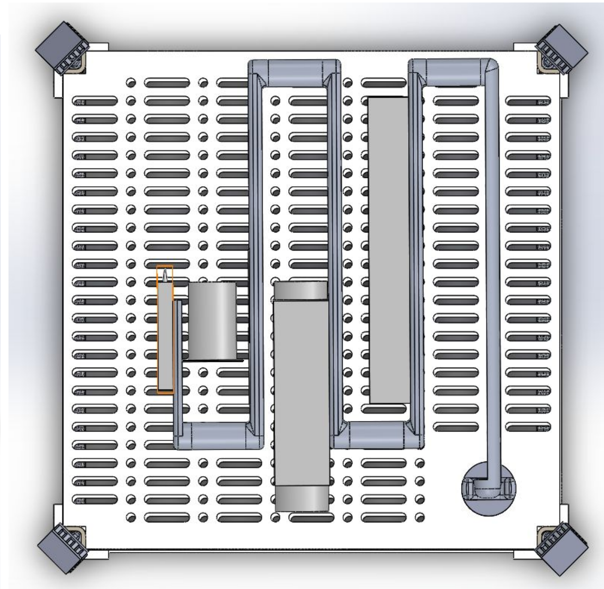
The third iteration of the lander has evolved to include a robotic arm on top in order to support the scientific objectives of the mission. Since, as mentioned in section 1.4, the TECP and AXPS instruments need to be close to or in contact with the lunar ground in order to function properly, and since the DAN instrument is most useful if it is able to observe a large area of ground, a robotic arm harboring all three instruments seemed to be the logical solution for using the scientific instruments to their full capacity.

Iteration 3 Descent Description

In the third iteration, the team decided PIE-L would have two thruster systems. PIE-L would leave its orbit at 20km above the surface of the moon and decelerate at as large an angle as possible. The lander would use its attitude-controlling thrusters to make the first two thrusts: one to exit its orbit and one to adjust its orientation at around 10km above the lunar surface. These thrusts will be simulated and timed.

After reaching a point where the team will have calculated that the lander will decelerate to 0m/s about 5 meters above the ground, it will start to fire its main thrusters. At 8 meters above the bottom of Shackleton Crater, PIE-L will deploy its legs and free fall the rest of the way to the bottom.

Iteration 4:

Iteration 4 Lander Description

The final design iteration takes into account material weight and instrument weight on the lander to realize the weight constraint. Lightening holes were placed across the instrument platform and the secondary platform to reduce weight as much as possible. Lightening cuts were also done in the 90 degree brackets to further reduce weight as well as changing the material to a magnesium alloy. Magnesium alloy has a smaller density value than aluminum thus makes it ideal for the lander. The lander feet were also redesigned to absorb more impact energy while also reducing weight. Inspiration was taken from carbon fiber structures that use honeycomb structures to reduce mass but maximize strength. Due to the nature of the lander dropping several meters above the ground, the lander feet were designed to reduce impact by creating a structure that would crumple. The secondary support leg was designed to help support the main leg from deflecting or taking too much stress during this impact.

Iteration 4 Descent Description

The change made to the final iteration was to perfect the ideation of the thruster system. Due to weight constraints the team reduces the system into one thruster system. The system will consist of 4 gimballed thrusters mounted to the bottom of the lander. The 4 smaller thrusters will be thrust vectored by an onboard computer that changes the thrusters' orientation during the descent. The descent will still involve an initial thrust to leave orbit, an adjustment halfway through descent, and a final deceleration to 0 m/s before free falling down to the 5m from the surface.

2.2. Evolution of Payload

Iteration 1

Science Objectives

Initially, the lander's science objectives were as follows:

1. Determine percentage of water in lunar soil at the bottom of the chosen crater
2. Test the water ice that is found for potability and organics
3. Measure radiation throughout the descent into the crater

These initial science objectives were chosen by the team because they would provide the information to both the lunar science community, who are interested in studying the moon, and the space exploration community and the US government, who are interested in using the moon as a resource or a potential site for a base.

Determining the percentage of water in lunar soil could provide an estimate of how much water there is on the moon, which is useful for understanding the moon's composition and for evaluating lunar ice resources. Testing the water ice for potability and organics could provide scientists with information about how life formed and how difficult it would be to process the water for human use, whether for consumption or for fuel. And measuring radiation throughout the descent into the crater, knowing that water ice can block some kinds of radiation, could provide insight into how water ice throughout the moon's crust protects the inside of a crater from radiation, which can be used for purely scientific purposes of determining distribution of water ice in the crust, and for exploration purposes of considering craters as a possible safe house for humans and other forms of life from radiation.

Instruments

For radiation detection, this iteration contains:

- the Radiation Assessment Detector (RAD), which measures high-energy radiation including particles, energetic ions of various elements, neutrons, and gamma rays(Hassler, n.d.-a).

For water detection, this iteration contains:

- Dynamic Albedo of Neutrons (DAN), which uses neutrons to determine depth and composition of H- and OH- bearing molecules(*DAN Instrument Information – MSL – Mars Science Laboratory*, n.d.-a).

For water testing, this iteration contains:

- The Microscopy, Electrochemistry, and Conductivity Analyzer (MECA) which has 3 instruments: the Thermal and Electrical Conductivity Probe (TECP), which could be used for water detection; the wet chemistry lab, which looks at salts; and microscope assembly, which looks at the texture of regolith grains(*Phoenix Mars Mission - Mission - Science and Technology - Spacecraft and Science Instruments - Microscopy, Electrochemistry, and Conductivity Analyzer (MECA)*, n.d.-a).
- COSAC, which detects and identifies organic molecules(*COmetary SAmpling and Composition (COSAC)*, n.d., *Ptolemy: An Instrument aboard the Rosetta Lander Philae, to Unlock the Secrets of the Solar System*, n.d.))
- Ptolemy, which detects isotope ratios of Hydrogen, Carbon, Nitrogen and Oxygen via gas chromatography and mass spectrometry, both of which would require the SD2 drilling system(*COmetary SAmpling and Composition (COSAC)*, n.d., *Ptolemy: An Instrument aboard the Rosetta Lander Philae, to Unlock the Secrets of the Solar System*, n.d.).

The reasons for changing our design and not proceeding with Iteration 1 are explained under the next section, Iteration 2.

Iteration 2:

Major Changes Summary:

- *No radiation detection*
- *No sample collection instruments*
- *Only TECP from MECA will be used (not the other two components of MECA)*

Science Objectives

The new science objectives in iteration 2 are as follows:

1. Verify the existence of water
2. Collect data on the depth and distribution of water on the moon

After long consideration, the team ruled out the radiation detection portion of the mission from Iteration 1 because detecting which radiation exists at different depths in a crater is not the most direct method of measuring for water ice, given other potential capabilities (such as in situ testing) that the lander has as a lander. However, given that neutron radiation may provide us with information about the water ice content of the crust since water (high in H) is effective at stopping neutrons, the team will keep the Radiation Assessment Detector (RAD) as a back-up instrument for the science payload if future iterations prove to be too heavy(*NRC: Radiation Basics*, n.d., *SD2* | *Rosetta*, n.d.).

Instruments
The team decided not to include the sample collection and analysis system from Iteration 1 because 1) drilling on the moon provides more technological challenges to solve due to the moon's low gravity, and 2) sample analysis instruments such as Ptolemy or COSAC require a sample collection drill, such as the R2D, which itself is about 5kg(*SD2* | *Rosetta*, n.d.). Although the R2D could potentially be miniaturized, the team decided that the main instruments must have flown before successfully, since this mission is not meant to prove the capabilities of new technology but to use flight-proven technology to characterize water on the moon. When considering that a 5kg drill alone takes up half of the lander's allocated mass, the team decided that the lander cannot afford to allocate that much mass solely for a sample collection system, and that the mass is best spent on instruments that do not require samples to be brought to them. Unfortunately, the drill-requiring instruments are the ones that can measure for both water potability, organics, and content, so the team's decision to not include a sample collection system not only ruled out some instruments, but also nullified the previous iteration's second science objective of testing the water ice that is found for potability and organics.

After exchanging emails with Dr. Michael Hecht (head of MECA for Mars Phoenix) for advice on what MECA is used for and whether it could help achieve the team's science objectives, the team decided to include just the TECP from the MECA suite, instead of the whole MECA suite (as Iteration 1 had) since the other instruments are only useful for looking at rocks that had been in contact with liquid water before (such as on Mars).

Of the original RAD, DAN, TECP (from MECA), COSAC, and Ptolemy:

- RAD was ruled out since the mission objectives changed
- COSAC and Ptolemy were ruled out because their accompanying drill was too heavy
- Most of the MECA suite was ruled about because it is not applicable on the moon.

So, in this iteration, the science payload contains the TECP from MECA and the Dynamic Albedo of Neutrons (DAN).

The reasons for changing our design and not proceeding with Iteration 2 are explained under the next section, Iteration 3.

Iteration 3:

Major Changes Summary:

- Alpha particle X-Ray Spectrometer (APXS) added to payload

Science Objectives

1. Verify the existence of water.
2. Collect data on the depth and distribution of water.
3. Collect data on the elemental distribution of the crater floor.

After considering the data that both DAN and TECP could provide (depth and distribution of -H and -OH molecules, and verification of water presence, respectively), the team decided that it would be useful to have more information about what the observed water reserves are found near, in hopes that this can provide guidance to future explorers looking for water and data for scientists who want to understand lunar water's interaction with its surroundings. Therefore, the third science objective was added.

Instruments

To meet the third science objective, the Alpha particle X-Ray Spectrometer (APXS), was added again. The APXS is capable of detecting elements, except for Hydrogen, in the rock or regolith that it is placed over, which is valuable in conjunction with the DAN, which does look for Hydrogen. In this third and final iteration, both DAN and the TECP remain from the previous iteration.

2.3. Evolution of Mission Experiment Implementation Plan

The iterations of the mission experiment implementation plan (2.3) go hand-in-hand with the iterations of the payload (2.2).

Iteration 1:

As mentioned in 2.2, the first iteration's science objectives were:

1. Determine percentage of water in lunar soil at the bottom of the chosen crater
2. Test the water ice that is found for potability and organics
3. Measure radiation throughout the descent into the crater

As mentioned in 2.2, the first iteration's instruments were:

1. the Radiation Assessment Detector (RAD)

2. the Dynamic Albedo of Neutrons (DAN), which uses neutrons to determine depth and composition of H- and OH- bearing molecules(*DAN Instrument Information – MSL – Mars Science Laboratory*, n.d.-a).
3. The Microscopy, Electrochemistry, and Conductivity Analyzer (MECA)
4. COSAC
5. Ptolemy

Implementation Plan

In this iteration, the RAD and the DAN sit on the main lander structure. The MECA is partially on the main structure, with a robotic arm to collect samples for the two sample-examining units, and with the TECP (regolith probe) on a foot of the lander. The COSAC and Ptolemy are on the main lander structure as well, with the SD2 drill collecting and preparing samples for both.

Iteration 2:

As mentioned in 2.2, the second iteration's science objectives were:

1. Verify the existence of water
2. Collect data on the depth and distribution of water on the moon

As mentioned in 2.2, the first iteration's instruments were:

1. the Dynamic Albedo of Neutrons (DAN)
2. Thermal and Electrical Conductivity Probe (TECP) from MECA

Implementation Plan

In this iteration, the DAN sits on the main base and collects data for only one location — it does not have the capability of moving to scan other nearby areas. The TECP is attached to a foot of the lander in order to reach the regolith and rock, but it, too, does not have the capability of moving to take data at another location.

Iteration 3:

As mentioned in 2.2, the third iteration's science objectives were:

1. Verify the existence of water.
2. Collect data on the depth and distribution of water.
3. Collect data on the elemental distribution of the crater floor.

As mentioned in 2.2, the third iteration's instruments were:

1. Dynamic Albedo of Neutrons (DAN)
2. Thermal and Electrical Conductivity Probe (TECP) from MECA
3. Alpha particle X-Ray Spectrometer (APXS)

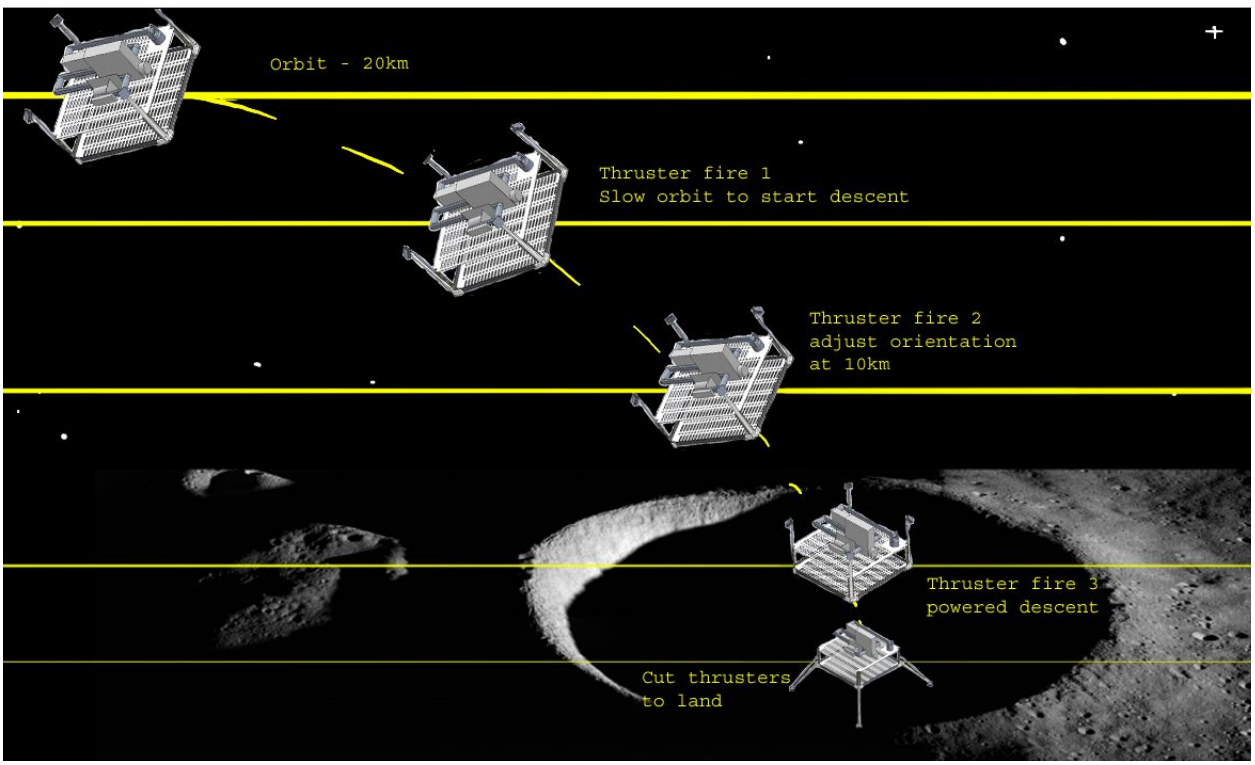
Implementation Plan
In this iteration, the payload will be integrated with the lander via a robotic arm. The TECP and the APXS will be on the tip of the arm in order to be able to touch the lunar ground, while the DAN will be higher up on the arm, so all three can move, but only TECP and APXS will be in contact with the ground.

3. Descent and Lander Design

3.1. Selection, Design, and Verification

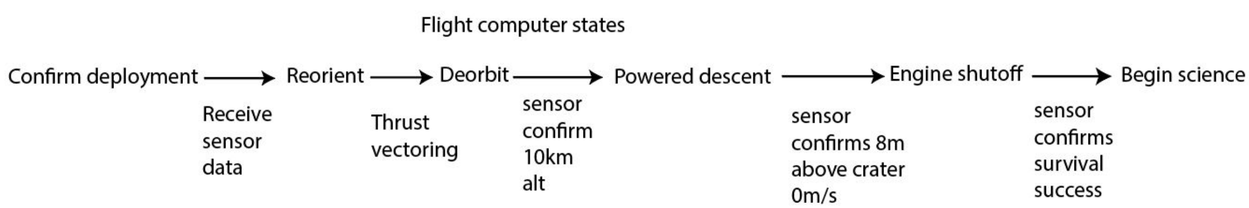
3.1.1. System Overview

Descent System

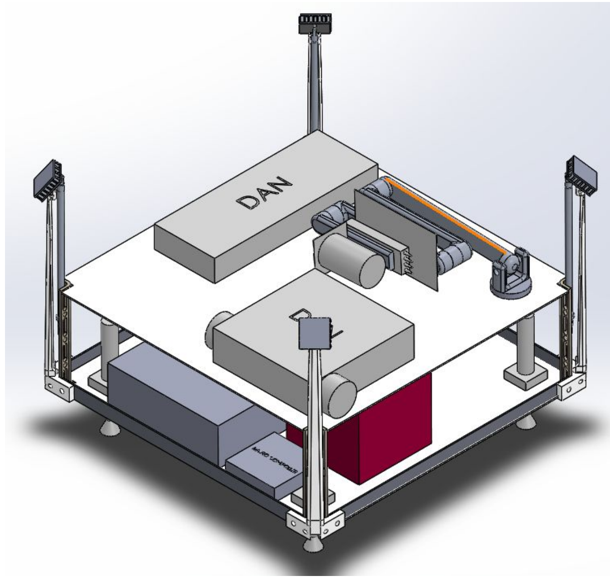


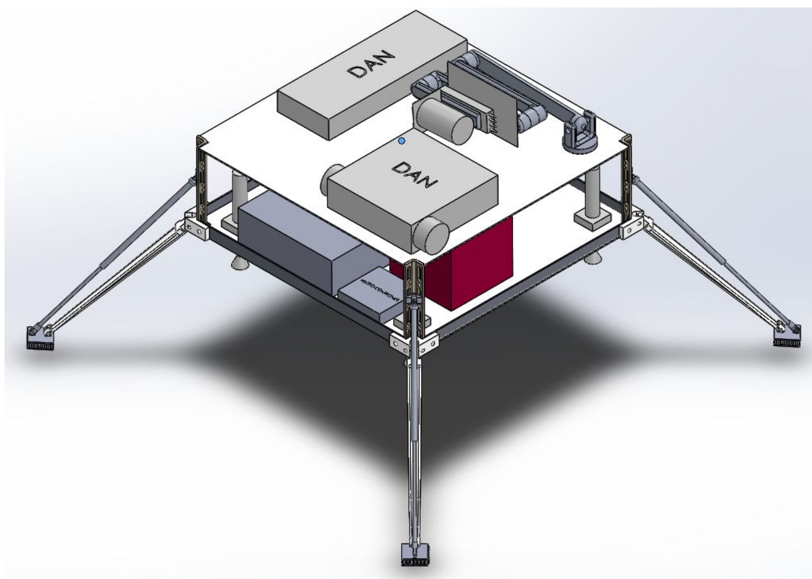
Above: PIE-L's descent to the Shackleton Crater (color added)

After being deployed off the orbiter, PIE-L will first assess its positions and orientation using its onboarding star tracker. The data will be assessed by the onboard computer to compute the optimal descent trajectory using Hohmann transfer. PIE-L will be using its thruster system in order to make a powered landing. To start its descent, PIE-L will fire its thrusters to perform a deorbiting burn. The thrusters will be thrust vectored to achieve optimal deorbit entry angle. The thrust vectoring will be controlled by the onboarding computer in a closed-loop feedback scheme. Since the landing is intended to be a powered landing rather than a ballistic landing, the entry angle will be shallow. At around half-way out of its orbit at 10 km, the thrusters will fire to reorient the lander and initiate the power landing phase. Once the star tracker confirms PIE-L is within the trajectory towards the mouth of Shackleton Crater, the lander will start to fire its thrusters to slow itself down. The lander's radar altimeter will initiate and replace the star tracker to track the altitude of the lander in the closed-loop feedback control system. The feedback control system will bring the lander to 0 m/s at 8 meters above the bottom of the crater. Once this is confirmed, PIE-L will shut down the thrusters and free fall the rest of the way to the surface while deploying its legs. The lander will land on the lunar surface at 5 m/s vertically. After the expected amount of time the descent and landing time has passed, the star tracker will transmit the star data above the lander. This will confirm the success and location of the descent and landing phase.



A powered landing in this manner is the best option on the lunar surface because powered landings have been successful in past lunar landings. The only difference between PIE-L and these past examples seems to be size. PIE-L is at least ten times less massive than the most recent example of a successful powered lunar lander: Chang'e 3. Even so, given the nature of the science payload, the team felt it would be safest to utilize the methods that are the most proven. Due to mass and volume constraints, a controlled descent was chosen as the team believed using mass and volume to create a landing structure able to survive a ballistic impact would be inefficient. Lastly, the team wanted the lander to be able to scan a larger vicinity than the initial landing zone. This was accomplished with the lander by allocating weight and space for a rotating robotic arm that would allow our lander to scan an area rather than one specific location.





Our lander was designed around maximizing the mass and volume constraint of 10kg and a 60cm cube thus our lander was constructed to have a box frame. At each corner a square cut out was made for a deployable leg to allow the legs to be confined within the 60cm constraint. The deployable legs were made with inspiration from the SpaceX Falcon 9 Heavy, which uses legs with a secondary support arm to help distribute and lessen impact forces when landing. These support arms will fit in a cut out of the main leg to reduce the volume used by the legs.The support arm uses telescoping tubes that will unfold by gas expansion. The gas will be released into the tubes which will push the telescoping tubes out and maintain their position. By using gas in the support arm, the arm is able to soften impacts due to the springiness of the telescoping tubes. In order to regulate the support arms from over deploying from an excess of gas, a strain gauge will be placed on each foot to measure the amount of deflection. Once the limiting value of deflection has been reached, the gas will be cut off from the support arm to prevent forceful over-deployment.

While the team tested the idea of having a lander that would be able to traverse the moon's surface, due to the landing site, space temperatures, lack of sunlight, and limited power sources, the team chose to have a stationary lander. To allow the science payload to be able to scan a sizable area for frozen water, the lander uses a pivoting robotic arm to maximize space and length. The arms will have a motor at each pivoting section to allow the arms to position themselves in any orientation needed to scan the area. In order to account for the lander tipping over when the arms and instruments are extended, the overall center of gravity will remain centered in the lander, with the weight of the battery, thrusters, and fuel tank counterbalancing the arms.

Power System

Nuclear options were considered at first since they solve two mission problems: dealing with the power and heating issues. Any place on the moon that still has ice is a considerably cold place, so being able to maintain working temperatures for the instrumentation is a serious issue. The team briefly considered the possibility of using radiation heater isotopes (RHUs)(*Radioisotope Heater Units*, n.d.) or multiple mission radioisotope thermoelectric generators (MMRTGs)(*Enhanced Multi-Mission Radioisotope Thermoelectric Generator (e-MMRTG) | Power Systems – NASA Radioisotope Power Systems*, n.d.) for their ability to deal with the aforementioned issues of powering and heating the lander, but it seems the availability of Pu-238 is extremely limited considering that Pu-238 is no longer being produced(*Economical Production of Pu-238: Feasibility Study*, n.d.) and the existing sources of Pu-238 are also extremely costly(*Space and Defense Power Systems Program Information Briefing*, n.d.).

The use of batteries is ideal for the lifespan of the lander in terms of cost and size, since solar is unattainable for places where ice exists on the moon, and nuclear is too expensive. Going with a battery as a power source we decided on a 1 kg lithium-sulfur battery that provides a total of 500 W to be used by our total system as this is enough to power the entire lander during its desired lifespan.

Control System

The Centaur Single Board Computer will be used to control the lander, and to enable the transponder to collect and send instrument data to the separate communication package, which will then send the data to Earth. There are pins/ wired connections from the instruments (and power system) connected to the board. It can communicate through the protocols available to the board, which includes: I2C, RS422 (which can be used with converter to translate to RS232), or some form of parallel communications with acknowledging “handshakes”.

Heating System

Maintaining operational temperatures for the instruments aboard PIE-L is a crucial task for mission success given that the landing site is in a very cold environment of 90 K. In order to ensure that the instruments are at an operational temperature we have decided to use a cartridge heater, located next to the battery, that will feed heated propylene gas into a loop pipe heating system that will branch off into the interior of the spacecraft as well as up the robotic arm which harbors the scientific components. This heating system will also work with a carbon dioxide gas which is injected into the interior compartment of the lander so that any warmth emitted by the electronics, battery, and the heat transported via the LHP system is absorbed by the thermally conductive gas. Temperature sensors will be programmed and installed at the loop pipe heating system ensuring that the interior does not reach temperatures outside of operating threshold for the components aboard the PIE-L.

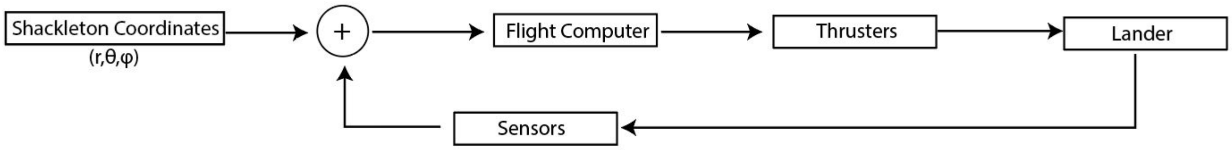
3.1.2. Subsystem Overview

Transponder Subsystem

The team will be using a modified Multi-Mode Standard Transponder (MST) to help transmit data, with the modifications emphasizing slowly on transmitting (and should cut down some of the weight). In the case it fails, an extra transponder of the same type is available for use. It connects to the main Centaur computer through the RS422 line (Tx/ Rx pins), and can either receive or transmit data from/ to the Centaur computer. When activated through a script (or similarly, an interrupt service routine), the MST will send the data packets collected from the instruments to the communication package provided, which will send the data to the orbitor then to Earth. The communication package will be sent by a trusted company.

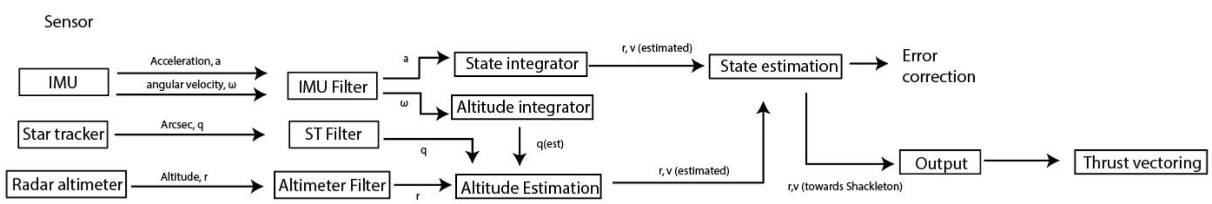
Thruster Subsystem

The lander will use four MR-103G thrusters mounted to a gimballed system at the bottom of the lander. The MR-103G thrusters are chosen because it is a lightweight thruster currently in production by Aerojet Rocketdyne and has flight proven record as altitude control thrusters(*Aerojet Rocketdyne In-Space Propulsion Data Sheets*, n.d.). The MR-103G is a monopropellant, hydrazine based thruster, which reduces the complexity of the system. The thrusters are gimballed due to weight constraints reducing the amount of thrusters that can be mounted on the lander. The gimballing enables the thrusters to be thrust vectored by the onboard flight computer.



Sensor Subsystem

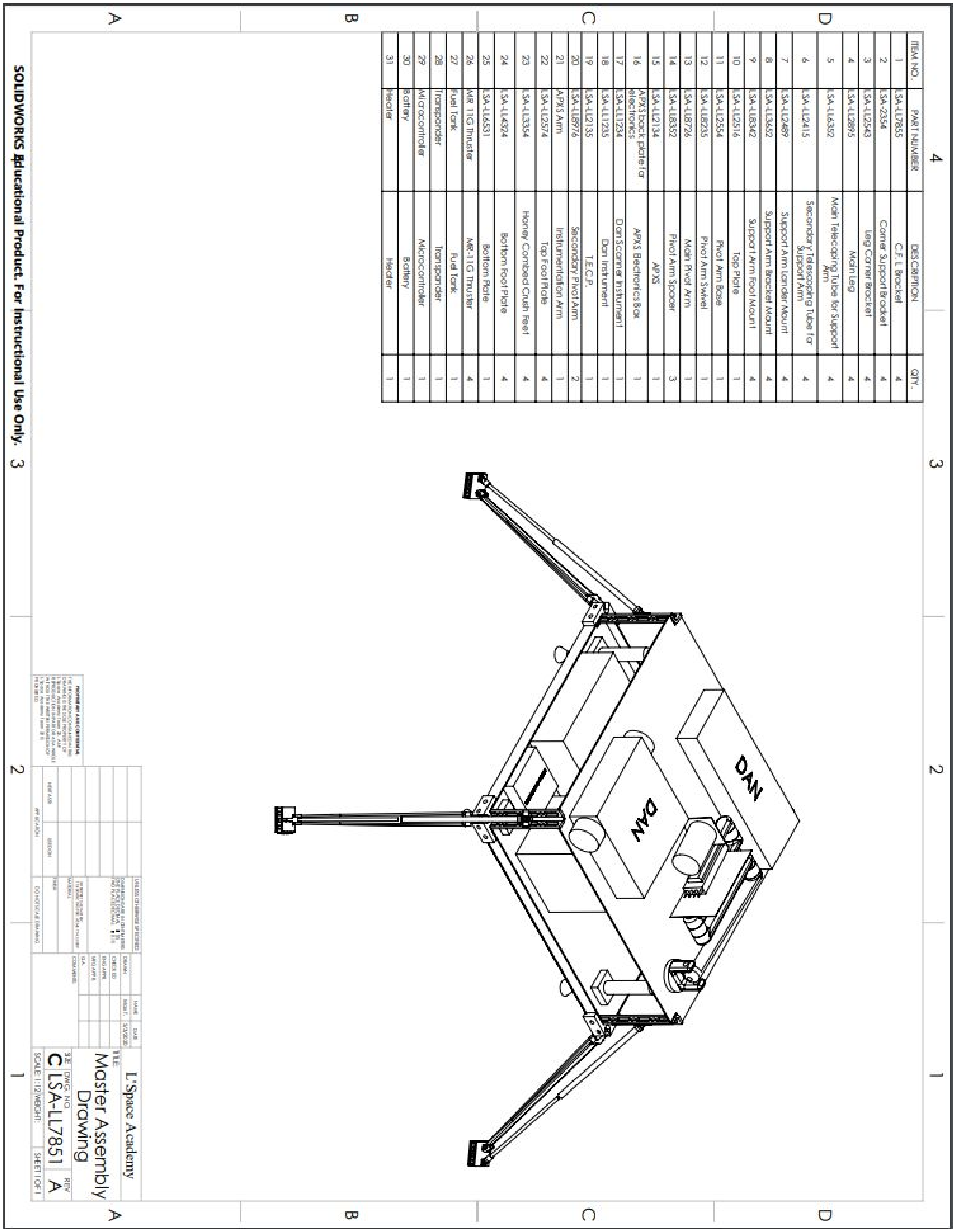
Because the descent and landing system utilizes a closed-loop feedback control scheme, the lander has several sensors to detect its orientation, position, altitude, velocity. For orientation and position, the lander will utilize the MAI-SS Space Sextant, a star tracker developed by Adcole Aerospace. This star tracker is chosen because of its weight of 170g and cheap cost(*MAI-SS Space Sextant*, n.d.). The Space Sextant has previously flown on cubesat missions, thus the team believes it's able to be used for the lander system. For velocity and acceleration measurements, the lander will utilize the Honeywell HG 1930 IMU. The HG 1930 is chosen because it is an aerospace grade IMU that weighs 160g. For radar altimeter, the lander will utilize an altered version of Honeywell KRA-405B Radar Altimeter. This altimeter is chosen because it is specifically designed for aerospace altitude measurement above ground.



Control Subsystem

To utilize the transponder and to organize data from the scientific instruments, the Centaur single board computer will be used for that purpose. It will be the “brain” of the lander. The board contains processors that enable the implementation of a feedback control system. The most common way for connection with the computer is through the RS422 connection. For instruments and sensors that require a RS232 connection, a converter will be used to sync it with RS422 standard. The computer has all the code, scripts, and interrupt service routines to receive data from the instruments then transmit it through the transponder to the communication package.

3.1.3. Dimensioned CAD Drawing of Entire Assembly



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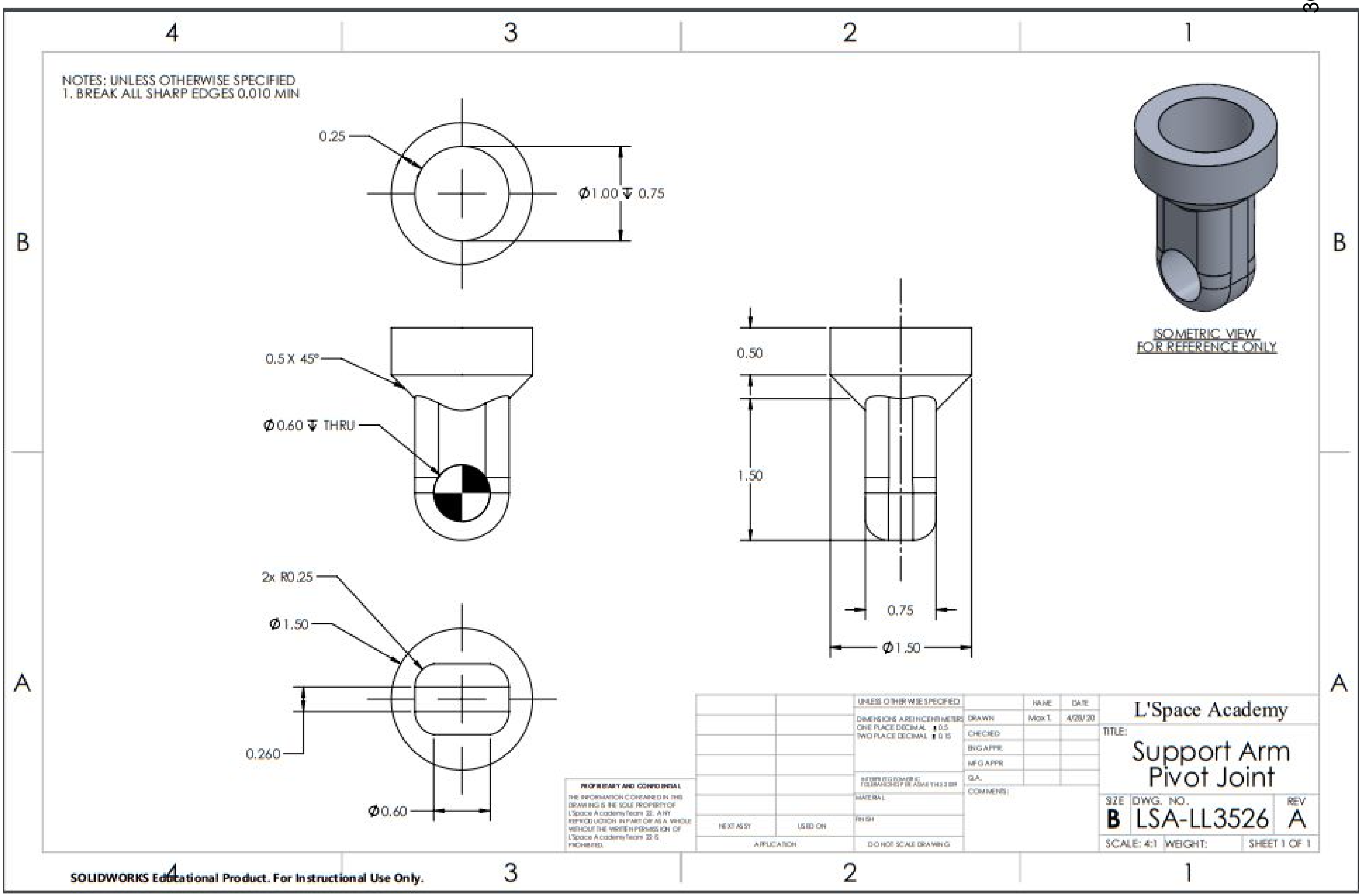
2	LSA-2354	Corner Support Bracket	4
3	LSA-LL2543	Leg Corner Bracket	4
4	LSA-LL2895	Main Leg	4
5	LSA-LL6352	Main Telecoping Tube for Support Arm	4
6	LSA-LL2415	Secondary Telescoping Tube for Support Arm	4
7	LSA-LL2489	Support Arm Lander Mount	4
8	LSA-LL3652	Support Arm Bracket Mount	4
9	LSA-LL8342	Support Arm Foot Mount	4
10	LSA-LL2516	Top Plate	1
11	LSA-LL2554	Pivot Arm Base	1
12	LSA-LL8235	Pivot Arm Swivel	1
13	LSA-LL8726	Main Pivot Arm	1
14	LSA-LL8352	Pivot Arm Spacer	3
15	LSA-LL2134	APXS	1
16	APXS back plate for electronics	APXS Electronics Box	1
17	LSA-LL1234	Dan Scanner Instrument	1
18	LSA-LL1235	Dan Instrument	1
19	LSA-LL2135	T.E.C.P.	1
20	LSA-LL8976	Secondary Pivot Arm	2
21	APXS Arm	Instrumentation Arm	1
22	LSA-LL2574	Top Foot Plate	4
23	LSA-LL3354	Honey Combed Crush Feet	4
24	LSA-LL4324	Bottom Foot Plate	4
25	LSA-LL6531	Bottom Plate	1
26	MR 11G Thruster	MR-11G Thruster	4
27	Fuel Tank	Fuel Tank	1
28	Transponder	Transponder	1
29	Microcontroller	Microcontroller	1
30	Battery	Battery	1
31	Heater	Heater	1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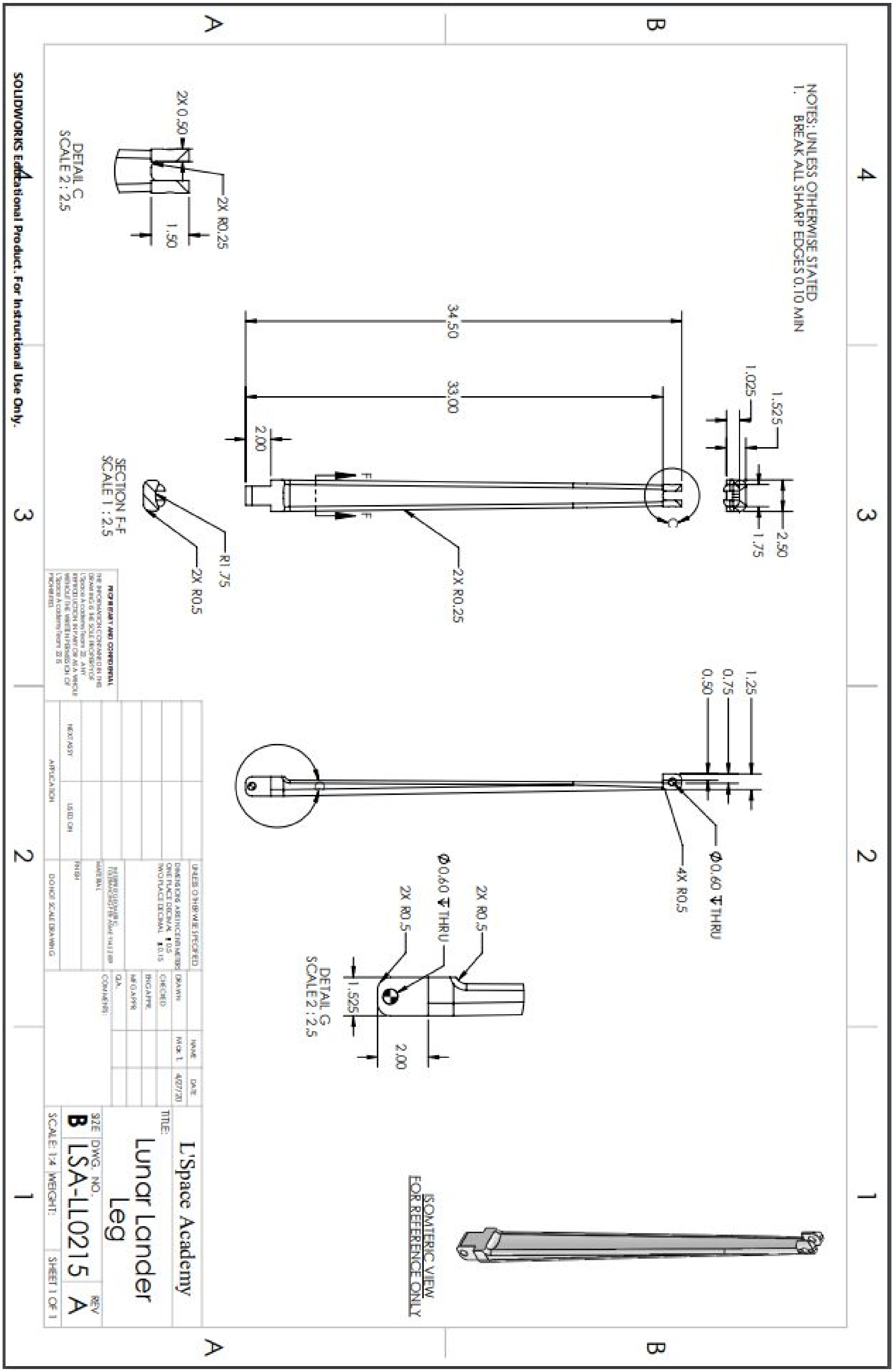
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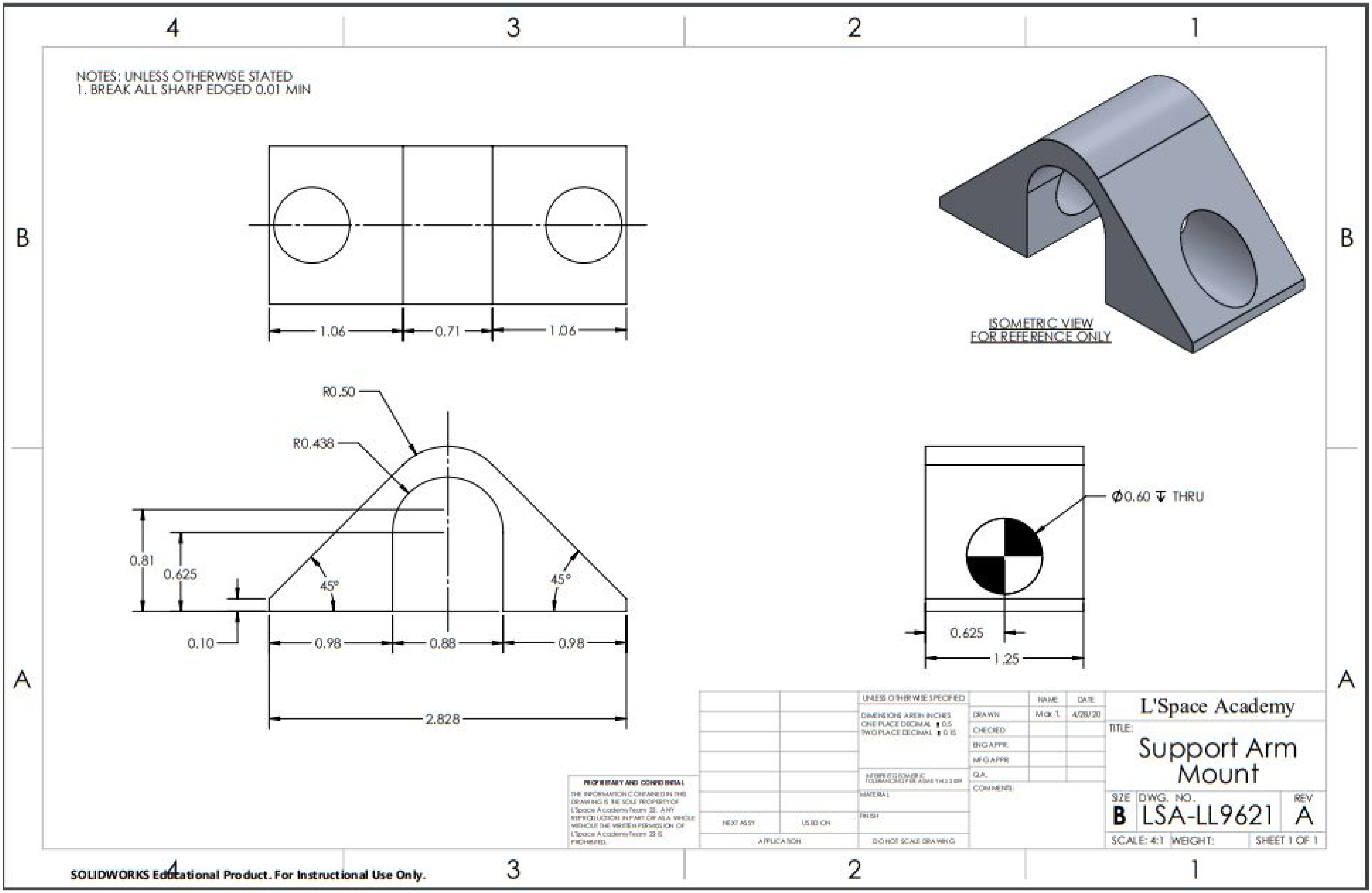
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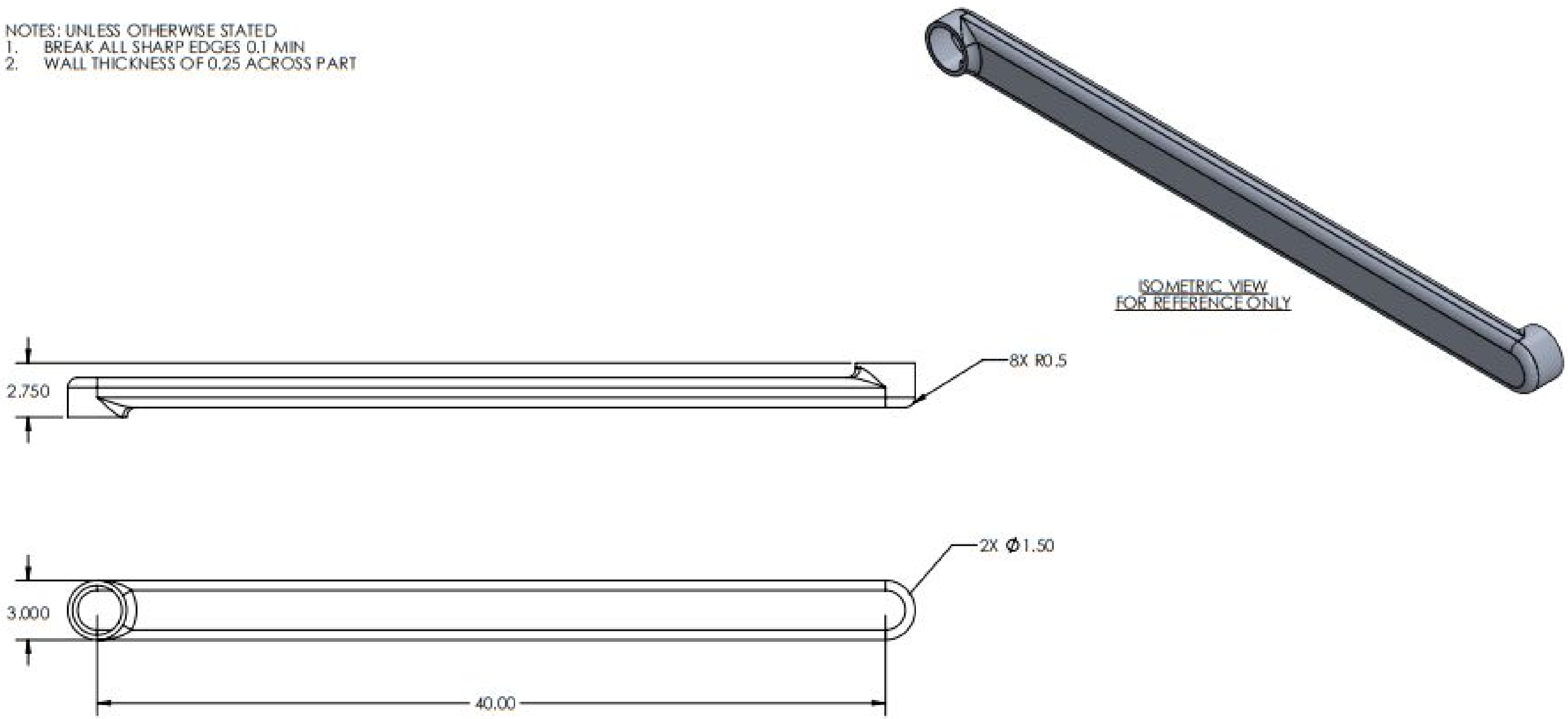

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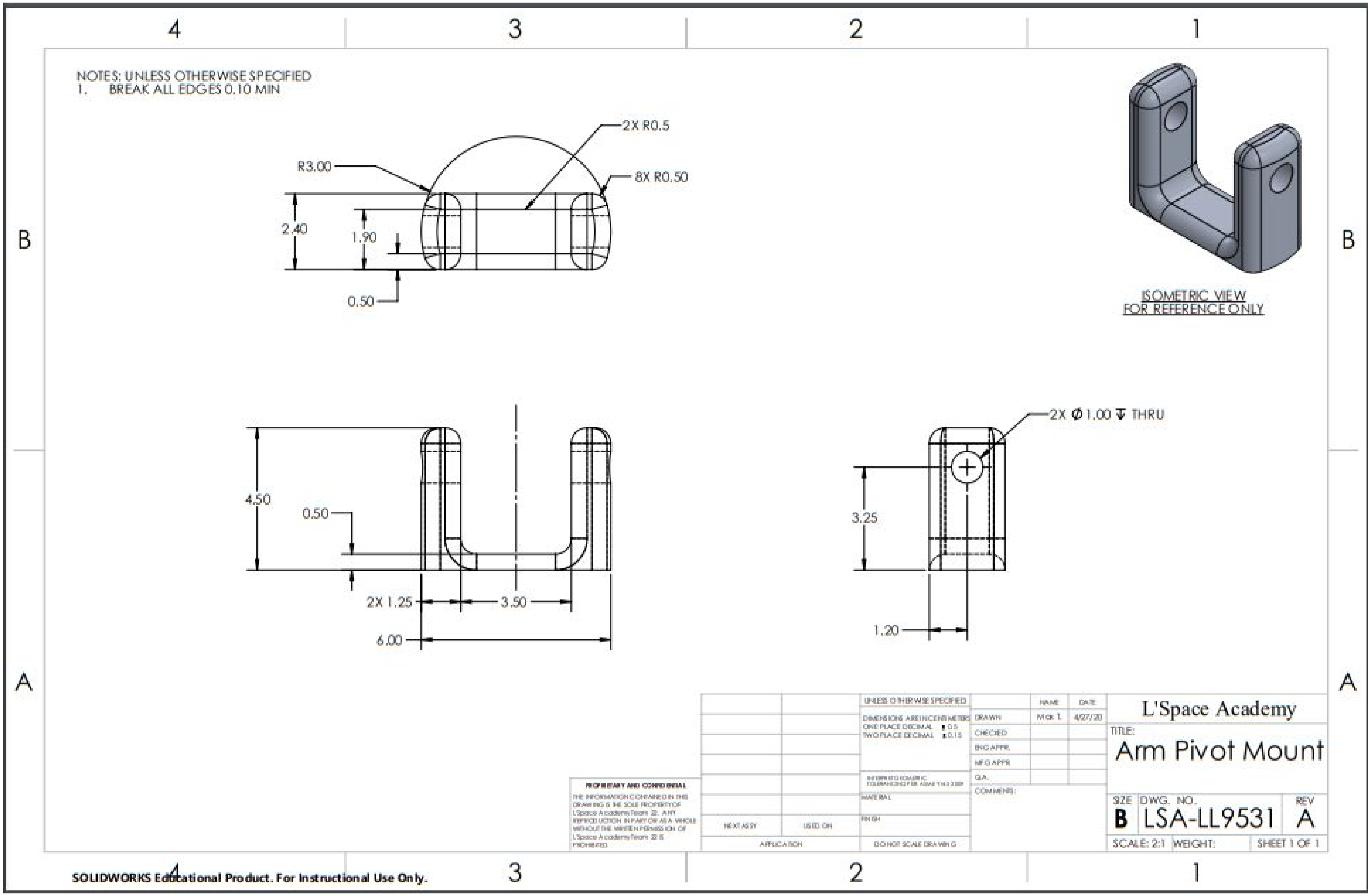

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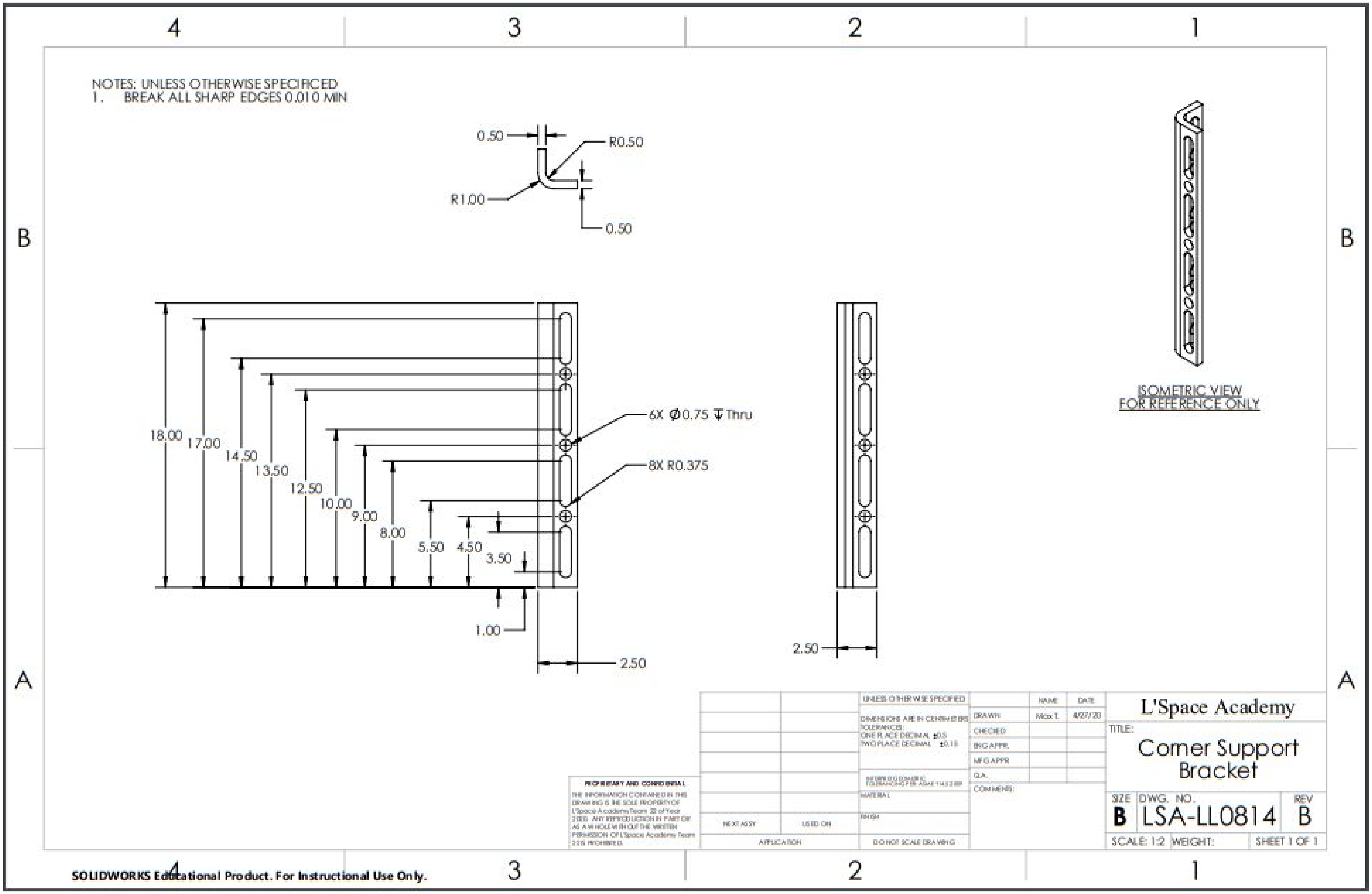
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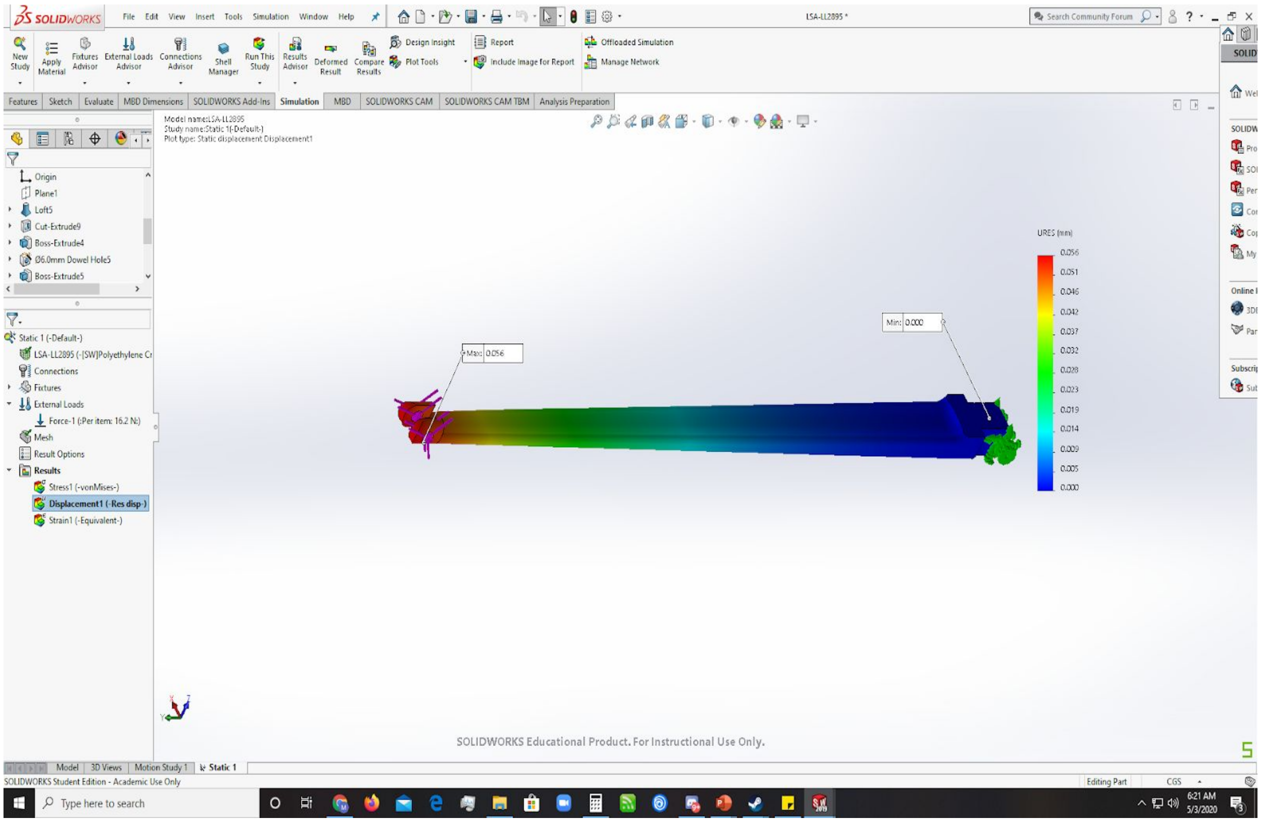
3.1.4. Manufacturing and Testing Plans

Since weight and compactness plays a large role in our lander design, a majority of the components will be custom made, making setup time and cost of parts much larger than normal. Most of the components for our lander can be made with normal machining practices such as a cnc mill and cnc lathe. The estimated man hours it would take to manufacture the components for our lander would be roughly 200 man hours given resources such as a cnc mill, cnc lathe, 5 axis trunnion, end mills, lathe bits, drills and metrology equipment. Most of this work can be made in a standard machine shop as it only needs standard machining practices, thus eliminating the need to outsource the manufacturing of custom components. The only components that would need to be outsourced are the legs of the lander, as their geometry would not allow for them to be made with standard machining practices and they would need to be injection molded.

In an attempt to test the components and ensure lander survival, Solidworks Simulation’s Finite Element Analysis was used to measure and test the stress, strain and deflection of components to make sure they can safely survive their environment. Fixed points were applied where components were mounted and unable to move and forces were applied in areas where the force would be the greatest. A baseline force was calculated that took into account the gravity of the moon 1.62 $\frac{m}{s^2}$ and the mass of the lander at 10kg which generates a force of 16.2N. Parts that were analyzed were the legs without the supporting arm to simulate the worse conditions as well as the feet of the lander as they will take the brute force of landing.



Critical load bearing, structural, and functional components of the lander can be built and tested to see if they are capable of handling their expected loads safely. Once components of the lander have been tested, the lander can be fully assembled and tested for complete function on Earth. After conducting Finite Element Analysis from Solidworks Simulation, our lander can first begin real world testing in test jigs to simulate the forces that will be applied before testing at the Surface Mobility Field Test sites. In order to reproduce similar surface environments to the moon, our lander can be tested in the same Geology Field Test (GFT) sites that were used to prepare lunar landers during the Apollo Missions. Specifically, the GFTs we would be using would be the sites where there have been previously conducted Surface Mobility Field Tests such as Moses Lake, Washington and Black Point Lava Flow, Arizona. To test and verify that our descent systems are functioning before launch, the control boards and thrusters can be fired and their resultant thrust output and pulses can be checked for correct measurements. Once the programming, control boards, and thrusters are able to match the simulated results, the descent system can be further tested for function in frigid environments that would simulate the temperature of outer space.

3.1.5. Validation and Verification Plans

In order to test the lander design, multiple simulations will need to be performed to evaluate the reliability and function of each lander component. To make sure the lander's structural integrity is sound, the team uses Solidworks Simulation to simulate the forces acting on the lander as well as ANSYS to simulate heat transfer that will be experienced by the lander as it descends to the lunar surface.

For testing the transponder, it will be sufficient to test communication with the transponder being in a far away distance from the receiver. The transponder can be connected to the Centaur board to verify data transfer. The test also proves to verify if the code is working or not based on the output data sent. To take it a step farther, the transponder can be placed in a payload sent to higher altitudes with a high altitude weather balloon. This will test the communication abilities and cold resistance of the transponder.

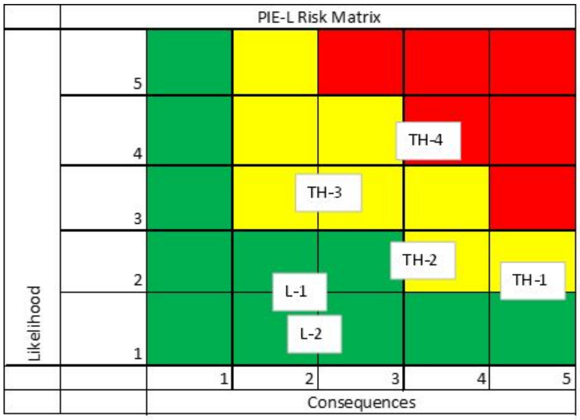
To verify the function of the lander and its instruments, tests can be done to see if the pivoting instrument arm is capable of supporting the load of the instruments rigidly and in a 360 degree motion in any orientation needed. The instruments can also be tested in a variety of environments and simulated moon surfaces for frozen ice on earth.

3.1.6. FMEA and Risk Mitigation

Descent and Lander FMEA And Risk Mitigation Chart

Function	Failure Mode	Effect	Sev	Cause	Occ	Design Controls (prevention)	Design Controls (Detection)	Det	RPN	Recommended Action
To provide a solid housing for scientific instruments	body of lander bends or twists	electrical components are exposed/compromised	8	brittle material used, weight requirement too strict	4	design with sturdy metal, strong geometric principles to ensure strength while still being lightweight	stress and vibration tests for components and assembly	1	32	Since parts are custom-made, research stress tests done on similar assemblies and come up with similar guidelines for testing for lander
				legs not deploying correctly						
	legs bend or break	lander topples, jolting contents and orientation of instruments	7	overly complicated design of legs	5	research tried and true designs used by historical moon landers	test on moon-like surface, but also on several "surprise" scenarios, such as cliff faces	7	245	Come up with a few different back up designs for legs so that testing can be implemented in quick succession if failure is seen in more than one area
To allow Lander to safely descend	Thrusters fire unevenly	Orientation of lander is incorrect upon landing	7	Electronics controlling thrusters not working	5	Possible design of lander with only one thruster, or many thrusters to mitigate risk of severe toppling	Test landing system for symmetry upon start-up	4	140	Work with engr team to see if robot arm can have additional use of righting the orientation of the lander
		Landing is fast and rough	7	Fuel for the thrusters compromised	4	utilize tried and true method of protecting fuel from elements including extremely low thermal energy conditions and radiation	research previous systems and previous detections of problems with thruster fuel release	7	210	Make sure that the lander can deflect harm to any systems
		Landing location is far from predicted								
		Lander misses crater altogether, resulting in mission failure								
	Thrusters fail to fire at all	Landing is at a severely high speed	9	Electronics controlling thrusters not working	5	Possible design of lander with only one thruster, or many thrusters to mitigate risk of severe toppling	Test landing system for symmetry upon start-up	4	180	Work with vendor to assure method of fuel injection and protection is what is standard for this type of spaceflight
		Landing location is far from predicted	9	Fuel for the thrusters compromised	4	utilize tried and true method of protecting fuel from elements including extremely low thermal energy conditions and radiation	research previous systems and previous detections of problems with thruster fuel release	7	252	(see above)
		Lander misses crater altogether, resulting in mission failure								
	Thrusters are not housed will into the lander	Thrusters fall out of lander when launched								

Legend	
SEV	Potential Severity
OCC	Likelihood of Occurrence
DET	Probability of Detecting and Avoiding
RPN	Risk Priority Number (SEV * OCC * DET)



Legend		
Risk ID's	Trend	Approach
TH - Thruster	^ UP	M - Mitigate
L - Lander	v down	W - Watch
	o unchanged	A - Accept
		R - Research

Trend	Rank	Risk ID	Approach	Risk Title
o	1	TH-1	R	Thrusters do not fire because fuel for thrusters compromised
o	2	L-1	A	Legs for lander bend or break
o	3	TH-2	M	Landing is rough because thrusters fire unevenly
o	4	TH-3	A	Landing is at a high speed because thrusters fail
o	5	TH-4	M	Orientation of science is incorrect upon landing
o	6	L-2	A	Electrical components are exposed because lander bends or twists

Given the event occurs, what is the magnitude of the impact to the PIE-L Program?						
	Level	1	2	3	4	5
	Technical	Minimal or no impact	Mod. Reduction, same approach retained	Mod. Reduction, but workaraounds avail	Major reduction, but workarounds available	Unacceptable, No alternatices exist
	Schedule	Minimal or no impact	Additiona; Activities required, able to met need dates	level 2 milestone slip of around 1 month	Level 2 milestone slip of over a month, or program critical path impacted	Cannot achieve Major Program Milestone
Consequences	Cost	Minimal or no impact	Individual system budget increase of less than 5%	individual system budget increase between 5 and 10 percent or program budget increase of 2 percent	individual System Budget increase of over 10 percent or pgram budget increase of over 5 percent	Individual System Budget Increase of over 15 percent or Program Budget increase of over 10 percent

What is the likelihood the situation or circumstance will happen?				
	Level	Probability	Probability (Safety)	...or - the current process...
	5	Near Certain 80%-100%	Likely to occur immediately	cannot prevent thiis event, no alternate approaches or processes are available
	4	Highly Likely 60%-80%	Probably will occur in time	cannot prevent this event, but a different approach or process might
	3	Likely 40%-60%	May occur in time	may prevent this event, but additional actions will be required.
	2	Low Likelihood 20%-40%	Unlikely to occur	is usually sufficient to prevent this type of event
Probability	1	Not Likely 0% - 20%	Improbable to occur	is sufficient to prevent this event

The above graphic is a risk matrix diagram for PIE-L's lander and descent system. The tables explain the numbers on the chart and their significance. From the chart it is obvious that the most severe risk at this point is that PIE-L may not be in the correct orientation to perform its duties. As reported, the team will attempt to mitigate the risk that the lander's data collection will be compromised by it landing in the incorrect orientation.

The team will continue to use this method to ascertain the severity of risks to the lander and descent system through to the launch of PIE-L in order to facilitate decision-making.

Thorough description of risks

*Risk TH-1 - Thrusters do not fire because fuel for thrusters is compromised***.** More information is needed about how the fuel for thrusters will perform in an environment where the lander is exposed to severe temperature fluctuations that it will experience upon descent. The consequences for this risk are high, because if the thrusters do not fire the lander could either suffer major damage as a result of not slowing down sufficiently enough to land softly or the lander could not exit orbit at all and therefore not accomplish its mission. The likelihood of this risk is low, because the thrusters the team is considering purchasing are touted as flight tested by the manufacturer. The team expects to work with the manufacturer on secure systems for the fuel to not experience temperature fluctuations.

*Risk TH-2 - Landing is rough because thrusters fire unevenly***.** The cause of thrusters firing unevenly may range from a miscalculation, a fuel injection problem (see above), a misinterpretation of orientation data. The results of any of these causes could lead to the lander spinning uncontrollably upon its landing or perhaps landing at an inopportune angle. The consequences of this risk are medium level because an uneven thruster fire can lead to a severe spinning or high velocity landing as well as missing the target landing site, but the consequences may also be quite mild, such as a mild spinning or slightly off the intended site. The likelihood of this risk is also low. The team plans to work with the manufacturer of the thrusters as well as test and simulate landing calculations to make sure that the risk is sufficiently mitigated.

Risk TH-3 - Landing is at high speed because thrusters fail. This risk is similar to the above two - thrusters may fail due to a computer malfunction, a manufacturing default, or some result of an unexpected gravitational or magnetic pulse. Because these outside influences are at some extent unknowable, this risk is difficult to mitigate and therefore must be accepted.

Risk TH-4 - Orientation of science is incorrect upon landing. This risk may be a result of a miscalculation or a misfiring/fuel injection inconsistency with the descent system. This is classified as likely, while the consequences are medium-level. The Engineering team going forward will work to create a situation where, upon landing in an incorrect orientation, the lander will be able to right itself through the use of its robotic arm, but like an insect on its back.

Risk L-1 - Legs for lander bend or break. If the lander's descent system fails in some way and leads to a harder landing than anticipated, parts of the lander, such as its legs, may break. Since the lander is meant to protect the science equipment and energy systems, the legs do not serve any function except to cushion the landing. If the legs or other parts are damaged in the process, the consequences are light to none. The likelihood is also low, considering the team's dedication to manufacturing a strong vehicle capable of protecting the team's science mission goals.

Risk L-2 - Electrical components/systems are exposed because of damage to lander. Should the lander come in contact with an unexpected surface and tumble or run into sharp rocks or fall onto something causing systems to be exposed, the consequences need to be researched and watched more fully. The team will need to seal its important systems (energy, science, and communications) against damage or dust particle interference. The science team reports that dust particulates are not a problem for its instrumentation, so therefore the consequences are low. Since the region in which PIE-L is landing is permanently shadowed, the hazards cannot be known, so therefore the likelihood is also unknown, so it will have to be an accepted risk.

3.1.7. Performance Characteristics and Predictions

The goal of the lunar lander, PIE-L (Preliminary Ice Exploration Lander), is to characterize water within Shackleton Crater. The mission's science objectives are to:

4) **Verify the existence of water.**
5) **Collect data on the depth and distribution of water.**
6) **Collect data on the elemental distribution of the crater floor.**

The following criteria describe baseline success for PIE-L in chronological order. For the bare minimum, each of these criteria must be met:

- PIE-L is within no greater than 10% of its proposed budget of $35 million
- PIE-L is manufactured in time for launch
- PIE-L accomplishes a controlled landing from its orbit without severe damage to its instruments.
- PIE-L lands within Shackleton Crater.
- Communication from the transponder with the mission team begins after landing on the moon and within PIE-L's life-cycle.
- At least one instrument successfully reads data from the surface of the moon and is able to communicate it back to Earth.

- Data is archived and able to be accessed by the public after its mission is over.

The following criteria describes the best case scenario for a very successful mission:

- PIE-L is within no greater than 5% over its proposed budget of $35 million
- PIE-L lands within 20 meters of its designated landing site.
- PIE-L accomplishes its landing with little to no damage to any of its instruments
- Communication from PIE-L's transponder is prompt and elucidating to PIE-L's current situation up until its life-cycle ends
- All three of PIE-L's instruments read as much data as there is available within reach of its robotic arm.
- Instrument data is able to answer all scientific questions about the presence of water in the craters on the moon's poles and other conditions of the moon's surface. These scientific questions include: Is there detectable water ice on the moon (that can be detected via lander, not just via satellite)? What is the depth and distribution of water in Shackleton? What kinds of elements (apart from H and O) are present near water ice deposits, and is there any correlation between nearby elements and increased water content?
- Data is archived and utilized greatly within the scientific and STEM educational community.

The following criteria define mission failure. If any one of the following happens, the mission is a probable failure:

- PIE-L goes over 10% of its proposed budget during development.
- PIE-L is not ready for launch in time for its proposed window
- PIE-L does not successfully launch from its orbiter.
- PIE-L is damaged heavily so that its instruments do not work.
- PIE-L's scientific instruments may work, but its transponder does not work.
- PIE-L's instruments return data, but the data is too vague to interpret.
- Data is not archived or shared.

Predictions of the Lander System

To some extent, the conditions within the landing site are unknowable, therefore the team based its design and predictions on the following known criteria:

1) The lander will be dropped from an orbiter at a height of 20km and at 2.38 km/s.
2) The lander will be exposed to extreme heat from the sun as well as extreme cold in the shadowed region of the crater.
3) The lander will not have access to solar energy whilst inside the crater.
4) The crater may have some surface conditions whereby the lander could be knocked around and damaged in some way.

The lander system will be able to behave as expected because the team has predicted how much stress the lander can handle and will have sufficiently mitigated risks posed to the lander to hinder its function, which is to protect and deliver the science instruments to where they can be effective. The team's testing plans will include testing stress under extremely cold and hot conditions.

Predictions of the Descent System

Since there are no fluctuations in weather in the moon's exosphere, the team is confident that, though the descent system may not be as mature as the design for the lander, there is more certainty that whatever is simulated or modeled on a computer during the critical design phase will be closer to reality. The vendor the team is looking forward to working with is also a trusted source for information and products. Therefore, the team predicts that the descent system is a solid plan.

Predictions of the Communications System

As long as there is power provided to the transponder and Centaur computer, there can be scripts made to boot automatically upon startup. Assuming the communication package and the lander (containing the transponder) don't land too far apart, communication can be established easily like any regular modem would be able to do. Also due to the rigorous pre-mission testing and the use of space approved transponders, computer, and power source the risk of these components failing is mitigated. The communication package, being sent by a separate and trusted company also reduces the risk of failure.

Steps were taken to make sure that the communication components fall under operating specifications. An example of this would be addressing the operating temperature by insulating the lander and designing heating elements that radiate the desired heat for the communication systems. Thus with all of these considerations, the team predicts that the communication systems will function during our mission.

Predictions of the Science System

Two of the instruments require direct contact with the ground and so their performance requires the robotic arm to deploy correctly. This risk is mitigated by having the robotic arm tucked safely away and resting against a flat surface on the lander throughout descent until deployment. This system will also undergo vigorous testing before launch to validate its reliability. In addition, each instrument will communicate with the main lander's computer, which will communicate back to Earth to confirm that each instrument is working.

Predictions of the Control System

Due to the many tests and simulations that the control system would undergo before being launched, the team is confident that the control systems will carry out their desired objectives. The lander's controls such as the deployment of the legs and supporting arms, thrusters, robotic pivot arm, and instrumentation will undergo vigorous real world testing to verify that our designs will work in various moon simulated environments. Measurements such as thrust, period of thrust pulses, positioning of the robotic arm and thrusters can be checked to match the correct mathematical results to ensure objective completion. Deployment of supporting arms and legs can also be checked before launch and the ability to stop deployment if supporting arms are already stiff from floor contact. With all of these and other various tests, the team predicts that the controls of the lander will function for the mission.

Predictions of the Power System

As other space reconnaissance missions have landed on the moon previously, use of pre-existing space approved technology was used for our lander. Thus instead of trying to reinvent the wheel, the team used a Lithium-sulfur battery due to it's previous usage on other missions. Using the data sheet of the battery, performance specifications were followed to ensure proper function of the battery during the mission. Once the type of battery was chosen, power requirements and mission runtime were factored in to choose a large enough capacity battery to work for the mission. To take into account unexpected risks in space, a battery that was capable of running 2x the needed amount was chosen.

3.1.8. Confidence and Maturity of Design

PIE-L is a mature design that has many iterations. The team and its specialists have put a lot of thought into the types of experiments that will prove that the lander and its systems will be effective in the environment of both space (on its descent) and its landing site.

Evolution Over Time

The team's decision whether the descent system should be ballistic or controlled was well-informed by the success of past lunar missions, especially the most recent successful controlled lunar landing, that of Chang'e 3. Based on the amount of missions that have succeeded versus failed, the team decided that a controlled descent would be best due to the precedent of success for such landings.

The descent and lander system started from inspiration from SpaceX and Chang'e, but evolved based on risk analysis and serious feedback from team input.

Because our lander and descent system have matured through iterations, the team is confident that its design is viable for the mission success criterion of data collection.

Analyses Performed

To analyse whether PIE-L's descent system will work, our team conducted comparisons to prior lunar missions and utilized only strategies that ended in successful landings. The team also defined success broadly. Shackleton crater is 20km in diameter, so our landing system only needs to be as precise as to land within that large area. Also, PIE-L does not have a self-transportation system or any very sensitive and breakable cameras or fine machinery as in other, more complicated missions. Since the criteria for mission success hinges on being able to collect data by being in contact with the lunar soil, it is only necessary to achieve a landing on the lunar soil such that the lander is in a position to use at least one of its instruments.

Tests to be Conducted

Tests the team will conduct to make sure that the lander is able to orient itself and descend correctly may include lifting the assembled lander with a crane and testing the thruster systems in a near-vacuum (to simulate lack of atmosphere on the moon) over different challenging surfaces (craggy rocks, a brittle surface, a lot of dust, etc.). The team will also test situations wherein a thruster does not succeed in firing and use of a backup system is necessary. If simulations show that our lander will likely be undamaged in even our worst-case scenarios, the team may also consider practicing worst case scenario drills with the lander or a mock-up lander in Earth's gravity.

If those drills are performed successfully, the team can be confident that the lander will land safely.

To test the launch from the orbiter is going to be more difficult and will most likely involve a combination of computer simulation and half tests from a mock-up of an orbiter.

3.2. Recovery/Redundancy System

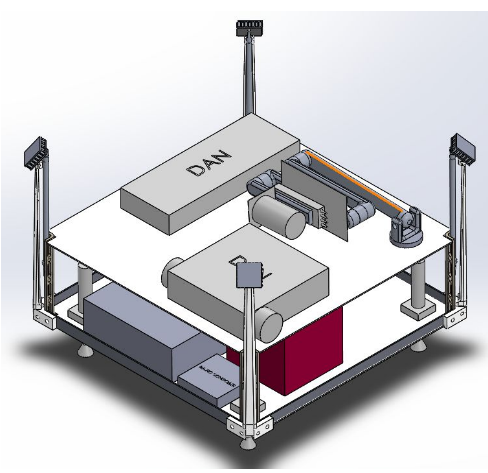
To satisfy the baseline requirements of the mission (see section 1.2.3), the following aspects of the mission require a back-up system: descent and landing, at least one scientific instrument, and the communication/transponder system. The descent and landing system needs a back up because in order for the mission to be a baseline success, the lander needs to land safely. The baseline success criteria states that at least one science instrument must function, so at least one science instrument will have a backup system. If the lander is unable to communicate its findings to Earth, the result will be mission failure, so the communication system will also have a backup plan.

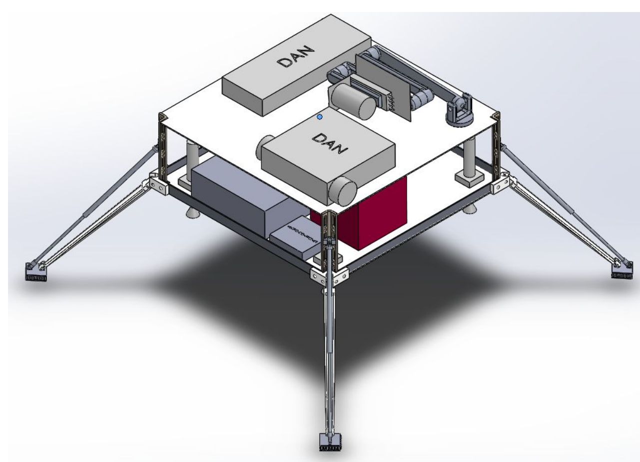
To back up the descent and landing system, should there be a failure in the thrusters causing them to fail (see section 3.1.6), the team’s response depends on the stage of the landing during which the failure occurs. If failure occurs during []... If failure occurs during the controlled descent after the spacecraft has deorbited, the lander will employ the emergency thruster to slow descent and inflate the airbag system to attempt to preserve the science payload.

To back up the science instruments should they encounter failure (see section 4.1.5), the team will include a spare DAN on the body of the lander. DAN was chosen because it is able to image and collect data from a distance and so if the arm is damaged and those science instruments fail the spare DAN will still be able to verify whether water ice exists inside the crater.

To back up the transponder system, the team will have a spare transponder in the lander. Should the main transponder not work (as confirmed by zero voltage detected by the computer in a routine loop), the secondary transponder will activate.

3.3. Payload Integration



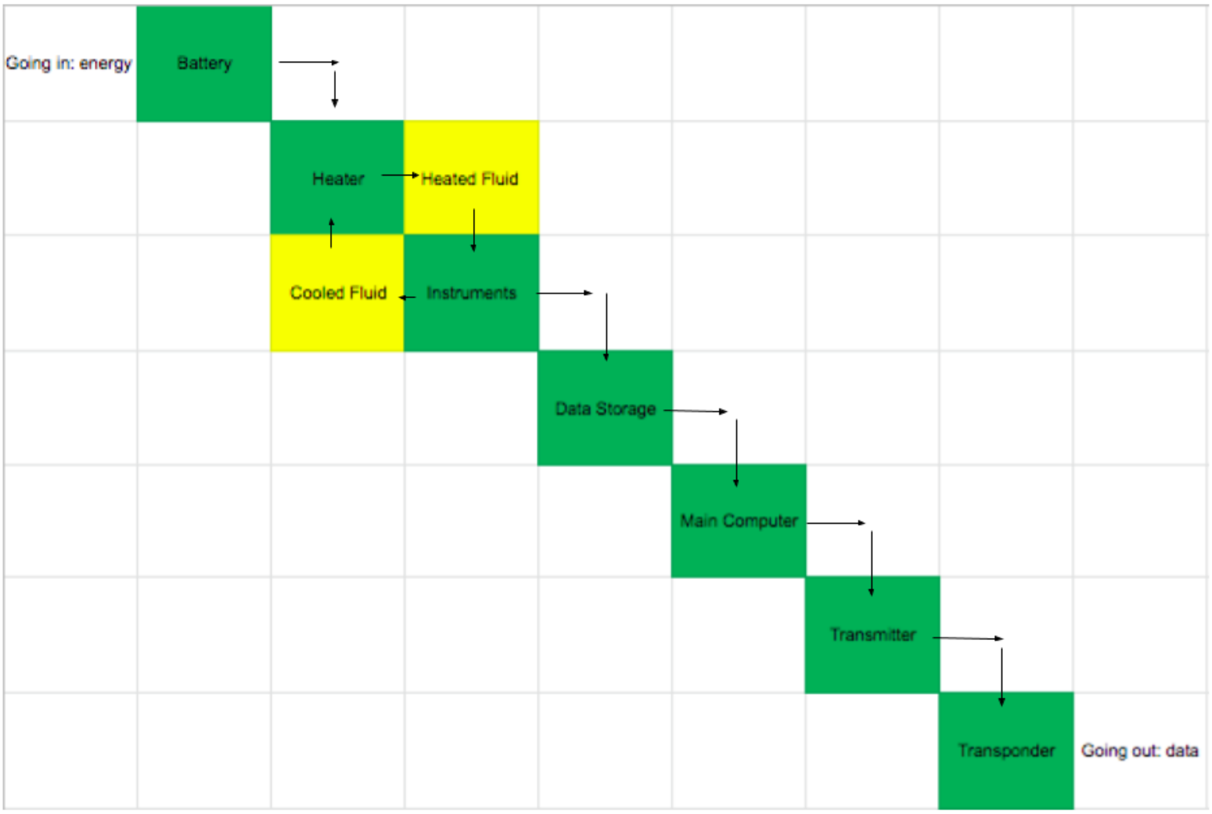


The payload is integrated onto the lander via a robotic arm. The robotic arm has the DAN instrument attached closer to the base of the arm, but still hanging over the lander, while the TECP and APXS are on the end of the arm, ready to be placed in contact with the lunar surface.

4. Payload Design and Science Experiments

4.1. Selection, Design, and Verification

4.1.1. System Overview - N^2 Chart



On-Board Computer

Options:
Any eligible lightweight flight-proven single board computer that can handle multiple processes and data. This includes the Centaur Single Board Computer and any microcontrollers with chips like the PIC32MX.

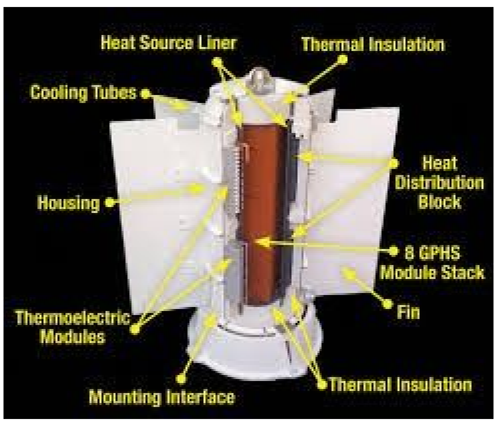
Selection rationale:
The computer must have ways/ protocols of listening to and transferring data (RS232, RS422, IC), along with being low

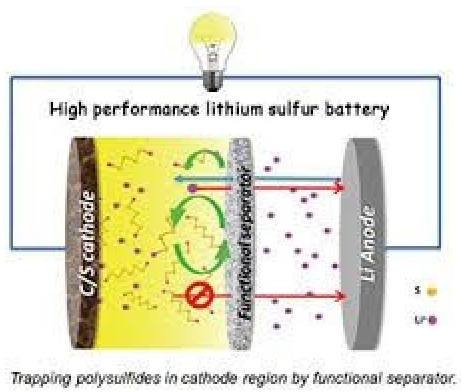
in power consumption. Must have a decent processor and some backup memory. Must have flight proven history. Must have dimensions smaller than lander volume.

Selected Concepts and Characteristics:
The team selected the Centaur computer for its flight proveness and low power consumption. It helps that the selected transponder will connect with RS422 protocol. Characteristics from available datasheet(*Single Board Computers*, 2017):

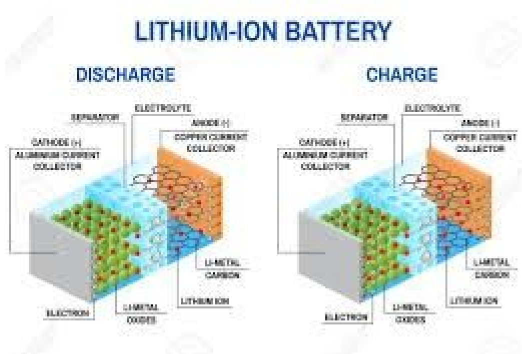
- GR712RC dual core LEON3-FT CPU
- 256MB SDRAM
- Up to 6 RS-422 UARTs
- SEU: < 1 error per 24 hour period

Power System
Options:





Trapping polysulfides in cathode region by functional separator.



Selection Rationale:

- Low cost
- High specific energy
- High energy density

Selected Concepts and Characteristics:

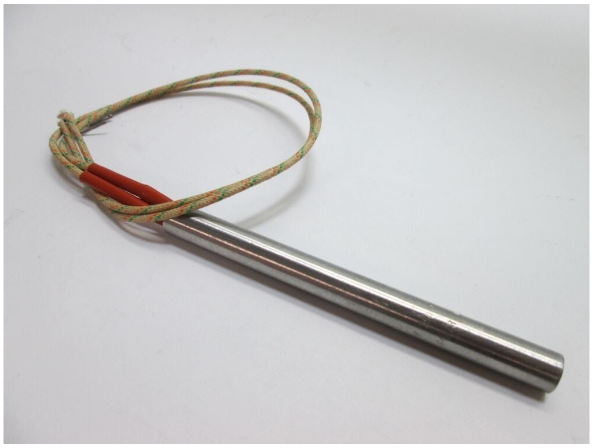
The final decision was to use a lithium-sulfur battery as it has a high energy density as well as a high specific energy.

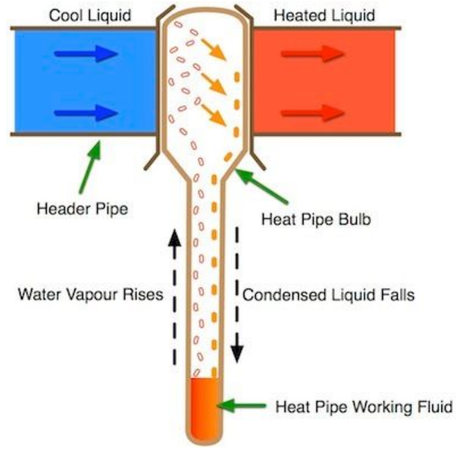
System Power Requirements

System	**Power (W)**	**Voltage (V)**
Lithium-sulfur battery	500 W	3V
TECP	1-3 W	5V
DAN	2.9 to 17.5 W	22-40V, depending on what it's doing
APXS	.5 to .624 W	28 V. Has its own power converter and filters since voltages needed are (+5 V digital, ±5 V analog and ±12 V analog)
Heating	~120 W	<40V (designed to use less than or equal amounts of voltage as the most intensive instrument)
Transmitter	7 W	<40V (designed to use less than or equal amounts of voltage as the most intensive instrument)
Centaur Board	4 W	
Robotic Arm	<17.5 W	<40V (designed to use less than or equal amounts of voltage as the most intensive instrument)
[Landing system]	20.61 W	28V

Thermal System

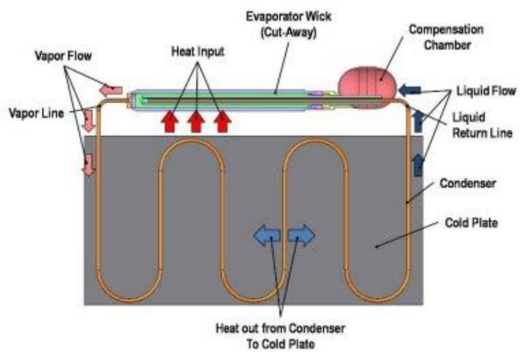
Options:

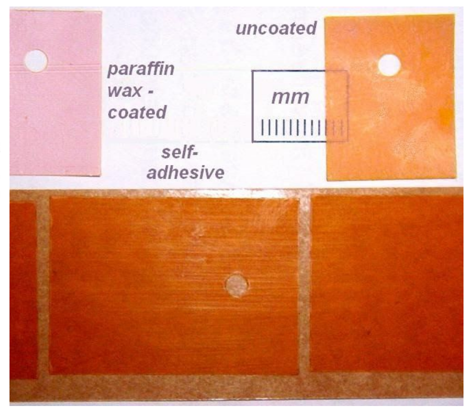




Cartridge Heater

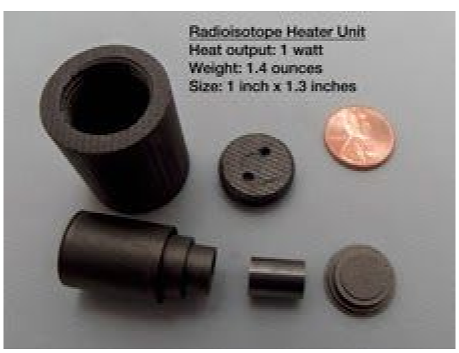
Heat Pipe

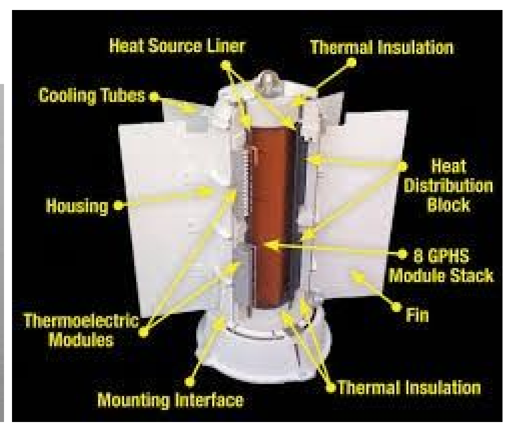




Loop Heat Pipe

Kapton





RHU

RTG

Selection Rationale:

- Low cost
- Power efficient
- Lightweight
- Range

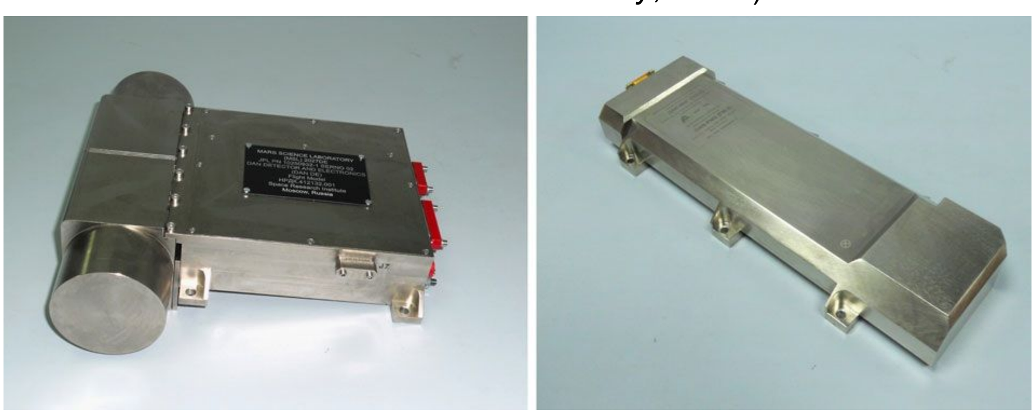
Selected Concepts and Characteristics:
The finalized selections are a cartridge heater near the center of the lander, keeping the central electronics at their operational temperatures. The cartridge heater also feeds into a loop heat system that runs along the robotic arm and is covered in kapton except for where the heat pipe passes the scientific instruments.

Data Acquisition System

Options:
As elaborated on in 2.2 and 2.3, the instruments that have been considered are:

1. The Radiation Assessment Detector (RAD), which measures high-energy radiation including particles, energetic ions of various elements, neutrons, and gamma rays(Hassler, n.d.-b). Image source: (Hassler, n.d.-b)

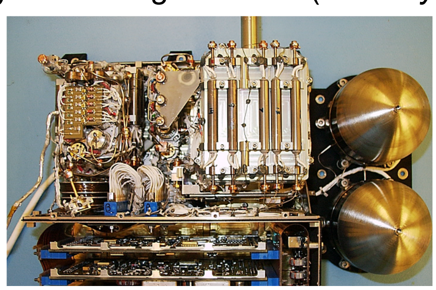
2. Dynamic Albedo of Neutrons (DAN), which uses neutrons to determine depth and composition of H- and OH- bearing molecules(*DAN Instrument Information – MSL – Mars Science Laboratory*, n.d.-a). Image source: (*DAN Instrument Information – MSL – Mars Science Laboratory*, n.d.-a)



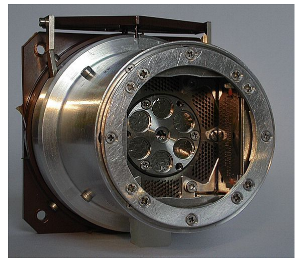
3. The Microscopy, Electrochemistry, and Conductivity Analyzer (MECA) which has 3 instruments: the Thermal and Electrical Conductivity Probe (TECP), which could be used for water detection; the wet chemistry lab, which looks at salts; and microscope assembly, which looks at the texture of regolith grains(*Phoenix Mars Mission - Mission - Science and Technology - Spacecraft and Science Instruments - Microscopy, Electrochemistry, and Conductivity Analyzer (MECA)*, n.d.-b). Below: the TECP from MECA. Image source: (*Phoenix Mars Mission - Mission - Science and Technology - Spacecraft and Science Instruments - Microscopy, Electrochemistry, and Conductivity Analyzer (MECA)*, n.d.-b)

4. COSAC, which detects and identifies organic molecules(*NASA - NSSDCA - Experiment - Details*, n.d.). Image source: (*COSAC | Rosetta*, n.d., *NASA - NSSDCA - Experiment - Details*, n.d.)

5. Ptolemy, which detects isotope ratios of Hydrogen, Carbon, Nitrogen and Oxygen via gas chromatography and mass spectrometry, both of which would require the SD2 drilling system. Image source: (*Ptolemy | Rosetta*, n.d.)



6. APXS, which detects the elemental composition of its surroundings. Image source: (*APXS Instrument Information – MSL – Mars Science Laboratory*, n.d.-b)



Selection rationale:
From a functional standpoint, the two main things the team prioritized were:

1. Can function in extreme temperatures and conditions (e.g., has flown before)
2. Can function without external sample collection/heating system

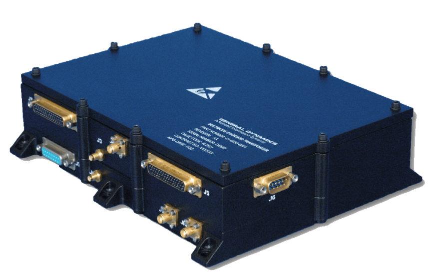
Additionally, the instruments selected had to meet our science objectives closely, and take advantage of the opportunities that a lander provides. For example, the team considered using the Radiation Assessment Detector to collect radiation data during the descent into the crater, but ultimately decided against it due to the fact that radiation is not tied closely enough with water ice characterization, and because the lander is capable of conducting in situ measurements, which is a rare opportunity.

The three instruments that best met these criteria were the TECP, the DAN, and the APXS.

Selected concepts and characteristics:
The concepts and characteristics of the instruments that ultimately ended up being selected were:

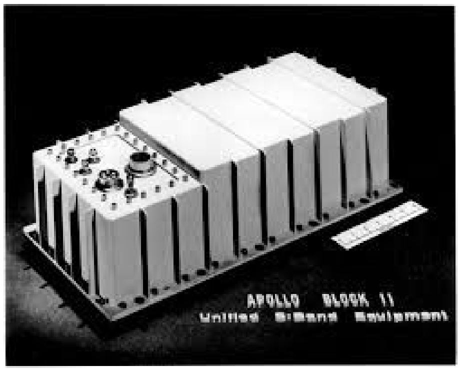
1. Can function in extreme temperatures and conditions (e.g., has flown before)
2. Can function without external sample collection/heating system
3. Conducts in situ measurements that require close proximity to the crater floor (which takes advantage of the lander's capabilities)
4. Can, collectively, fulfill the science objectives of
    a. Verifying the existence of water.
    b. Collecting data on the depth and distribution of water.
    c. Collecting data on the elemental distribution of the crater floor.

Communications System



Options being considered:
Multi-Mode Standard Transponder (MST), or some form of Unified S-Band transponder/ system.

Since the team only needs a transmitter, it may be modified for a lower weight and focusing more on transmission.
There will be some part of the budget dedicated to researching this modification.



Selection rationale: It must be an established transponder that has been used before, works in practice, and it should not be too bulky or heavy. Transponders like the Unified S-Band used in Apollo missions are too big. The MST has worked for 50+ years for a variety of commercial purposes. It uses the S-Band (like with previous transponders) and is affordable and compact. It is also flexible with multiple modulation modes.

Selected concept and characteristics:
The team will use the Multi-Mode Standard Transponder (MST), based on the reasons above.
Characteristics(*Multi-Mode Standard Transponder (MST) - General Dynamics Mission Systems*, n.d.):

- Operating Frequency: 2200 to 2300 MHz
- Frequency Stability: < 0.5 ppm,0 to +50º C

4.1.2. Subsystem Overview

The payload will meet the mission's scientific objectives of 1) verifying the existence of lunar water ice 2) collecting data on the depth and distribution of water on the moon and 3) gathering data on elemental distribution on the crater floor.

The size of the payload and landing structure will fit into a 60x60x60cm cube, per mission constraints. The total volume of the science payload is 4,960.366 cubic centimeters (out of 216,000 cubic centimeters for the whole lander), and the total mass of the science payload is 5.17kg.

As mentioned in 4.1.1, the payload consists 1) a power generating system; 2) a thermal system; 3) a data gathering system (the TECP, DAN, APXS and associated electronics); 4) a communications system.

Power Generating System

Since the possibility of radioactive sources of power are unavailable to anything except for flagship missions and no sunlight reaches the bottom of Shackleton Crater the best solution was to use a battery. The final decision was to use a lithium-sulfur battery since they have a high energy density and a high specific energy which allows for a high value of energy stored while having a low weight.

Thermal System

For the thermal system on PIE-L we decided on using a cartridge heater hooked into a loop heat pipe (LHP) system. This system will be placed on the walls of the lander in order to maintain operating temperatures for the circuitry, transponder, and battery. The LHP system will also loop up the arm which will provide heat to the instruments that will be making measurements. This cartridge will be hooked up to a thermal control system which will make sure the temperature inside the lander does not exceed operating temperature threshold on both extremes.

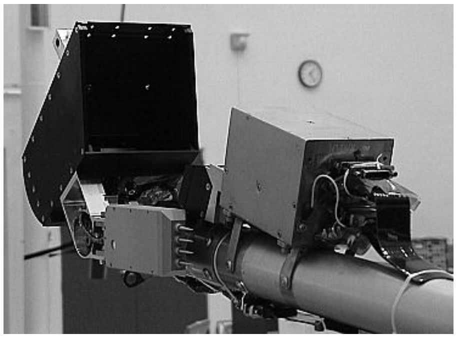
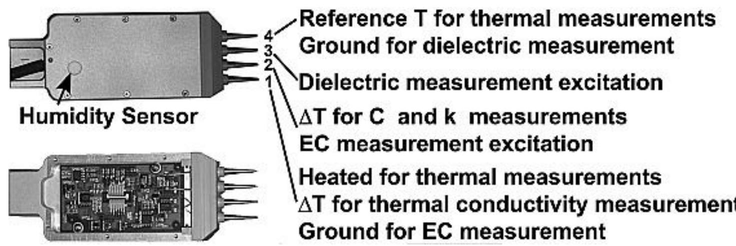
The interior of the lander will also be filled with carbon dioxide which will act as a thermal conductor. This can help mitigate heat loss due to the cold environment at Shackleton crater. PIE-L will also have aerogel and kapton to act as thermal insulators to trap the heat generated by the LHP system for the circuitry, transponder, the cartridge heater, and battery.

Data Gathering System

	Instrument	Size (must not exceed 60 cm in any direction)	Volume (cm^3)	Weight (kg)	Voltage Required	Power Usage	Objective 1: Water Existence Verification	Objective 2: Amount/depth of hydrogen	Objective 3: Elements near water ice reserves
	Dynamic Albedo of Neutrons (DAN)	(12.5 x 4.5 x 33.8 cm) + (20.4 x 6.1 x 21.2 cm)	4539.378	4.7	22-40 V	2.9 to 17.5 W	🟢	🟢	🔴
	Alpha Proton X-Ray Spectrometer (APXS)	(it is a cylinder with a 5.3cm diameter and 8.4cm height, with a 6.8cm thin square plate on the end — for calculation, thickness of the plate is assumed to be .1cm) + (electronics are 17cm x 10cm x 1 cm)	359.94	0.37	28 V	.5 to .624 W	🟡	🔴	🟢
	Thermal and Electrical Conductivity Probe (TECP)	(1.664 cm x 4.064 cm x 11.876 cm)	80.311	0.1	5 V	1 to 3 W	🟢	🔴	🔴
Alotted			216000	10					
Sum			4979.629	5.17					
Amount Left			211020.371	4.83					
	KEY								
	🔴	Does not contribute to science objective							
	🟡	Partially contributes to science objective							
	🟢	Fully meets science objective							

Thermal and Electrical Conductivity Probe (TECP)

To verify the existence of water, the payload contains a Thermal and Electrical Conductivity Probe (TECP), a standalone part of the Microscopy, Electrochemistry, and Conductivity Analyzer (MECA) instrument which has flown on the Mars Phoenix Lander(*NASA - Microscopy, Electrochemistry, and Conductivity Analyzer
built by the Jet Propulsion Laboratory*, n.d.). The TECP, using in situ measurements of dielectric permittivity (capacity of holding an electrical charge), electrical conductivity, temperature, thermal conductivity, volumetric heat capacity, and relative humidity, can confirm the existence of water ice in regolith(Zent et al., 2009). The instrument It collects data via 1.5cm needle-like probes that are inserted into regolith(Zent et al., 2009). The whole device has a volume of 80.311 cubic centimeters (1.664 cm x 4.064 cm x 11.876 cm)(Zent et al., 2009). According to Dr. Michael Hecht, who was the project lead for the Microscopy, Electrochemistry, and Conductivity Analyzer (MECA) instrument suite which includes the TECP, the TECP weighs under 100g, requires a 5V input alongside the PIE-L team's estimation of 1 to 3 W, and puts out serial data on an RS232 line(*Phoenix Mars Mission - Mission - Teams - Michael Hecht*, n.d.-b).

Left: The TECP mounted on the Robotic Arm of the MSL. Right: A diagram displaying the TECP's functions.

Dynamic Albedo of Neutrons (DAN)

To examine the depth and distribution of water beneath the surface of the lander, the payload contains the Dynamic Albedo of Neutrons (DAN). The two part instrument, a veteran of Curiosity, operates by pulsing high energy neutrons from one part (the Pulse Neutron Generator) of the instrument into the ground, while the other part (the Detectors and Electronics) detects changes in the reflection of the beam, determining subsurface Hydrogen presence up to .5 meters below the surface(I. Mitrofanov, n.d.)(NASA/JPL-Caltech, n.d.). It can operate at about 3 feet above the surface and is capable of detecting water content in regolith at as low as .1%(I. Mitrofanov, n.d.)(NASA's Mars Exploration Program, n.d.). The DAN pulse neutron generator has a volume of 1906.875 cubic centimeters (12.5 cm x 4.5 cm x 33.9 cm), a mass of less than 2.8kg, requires a 22-40V power supply, while the detector and electronics component has a volume of 2613.24 cubic centimeters (20.4 x 6.1 x 21.0 cm), a mass of less than 1.9kg, also requires a 22-40V power supply(Litvak et al., 2008). Based on Table 1, the Pulse Neutron Generator component requires between .1 W and 13 W when it is on, depending on what operation it is fulfilling, while, based on Table 2, the Detectors and Electronics component requires between 2.8 and 4.5 W, also depending on what operation it is fulfilling.

Table 1 DAN/PNG (flight unit) parameters

Parameter	Value
Max Dimensions	125 × 45 × 338 mm
Mass	2.6 kg
Energy of emitted neutrons	14.1 MeV
Number neutron per pulse	1.34×10^7
Total number pulses can be emitted per life time	$>10^7$
Duration of neutron pulse (FWHM)	<2 microseconds
Frequency of pulsing	From single pulses up to 10 Hz
Power in duty mode (power on)	0.1 W
Power in enabling mode (ready to pulse)	1.4 W
Power in pulsing mode	13 W
Operation temperature range	[−40, +50] °C
Survival temperatures	[−55, +75] °C
Input Voltage range (Normal operations)	22–36 V
Input Voltage range (Surviving)	0–40 V
Readiness to operate after switching power on	<2 sec
Warranty (life time of neutron tube)	3 years or 10^7 pulses

Table 1, depicting specifications for the DAN pulse neutron generator (PNG) unit. Source: (Litvak et al., 2008)

Dynamic Albedo of Neutrons Experiments 567

Table 2 DAN/DE (flight unit) parameters

Parameter	Value
Max Dimensions	204 × 61 × 212 mm
Mass	2.10 kg
Number of detectors	2 (CTEN and CEN)
Neutron energy (detected neutrons)	<1 keV (CTEN detector) 0.4 eV–1 keV (CEN detector)
Number of spectra channels per each detector	16 (linear)
Time scale per each detector	64 (logarithmic)
Duration of lowest time bin	2 microseconds
Spatial resolution	<1 m
Power in passive mode	3.7 W (22 V)–4.5 W (36 V)
Power at standby mode	2.8 W (22 V)–3.5 W (36 V)
Warranty	5 years
Operation temperature range	[−40, +50] °C
Survival temperatures	[−55, +70] °C
Input Voltage range (Normal operations)	22–36 V
Input Voltage range (Surviving)	0–40 V
Readiness to operate after switching power on	<1 sec
Warranty (life time of neutron tube)	3 years

Table 2, depicting specifications for the DAN detector and electronics (DE) unit. Source: Litvak et. al., 2008

Alpha particle X-ray Spectrometer (APXS)

To collect data on the kinds of elements that are at the bottom of a lunar crater, in order to determine if there's a correlation between some elements and the presence of water ice (in combination with the other instruments), the payload contains an Alpha particle X-ray Spectrometer (APXS), which uses both X-rays and alpha rays to observe(*APXS Instrument Information – MSL – Mars Science Laboratory*, n.d.-b). Several iterations of the APXS have flown before on missions including Curiosity, Pathfinder, Spirit, and Opportunity(*APXS Instrument Information – MSL – Mars Science Laboratory*, n.d.-b). The APXS itself is .25kg and 189.94 cubic centimeters in volume (it is a cylinder with a 5.3cm diameter and 8.4cm height, with a 6.8cm thin square plate on the end — for calculation, thickness of the plate is assumed to be .1cm) while its accompanying electronics are .12kg and 170 cubic centimeters in volume (17cm x 10cm x 1 cm)(Rieder et al., 2003). It can detect most chemical elements on the surface that it examines except for Hydrogen(*Mars Pathfinder Instrument Descriptions*, n.d.-b). It makes observations of how much of each kind of element is present by scanning rocks and soil that are right next to it(Gellert, n.d.-a). The instrument requires a battery that is ideally 28V (Rieder et. al., 2003). Data is stored in a 32 kilobyte SRAM in the main electronics and transferred via RS 422 link (Rieder et. al., 2003). For the sensor head, the power necessary is between .3 W and .324 W (as calculated from Table 1). For the main electronics, the power necessary is between .2 W and .3 W (as calculated from Table 2). The shortest time that APXS can take to make a measurement is 15 minutes, while the longest can take up to 8 hours (for example, when the alpha mode is used to detect Carbon)(Rieder et al., 2003). The APXS derives voltage from the board battery (28V) and uses between 5 and 12 V (generated by its own power converter)(Rieder et al., 2003).

Table 1. APXS Sensor Head, Including Door Mechanics, Microswitches, an X-Ray Channel, Two Alpha Channels, and Tantalum Shielding

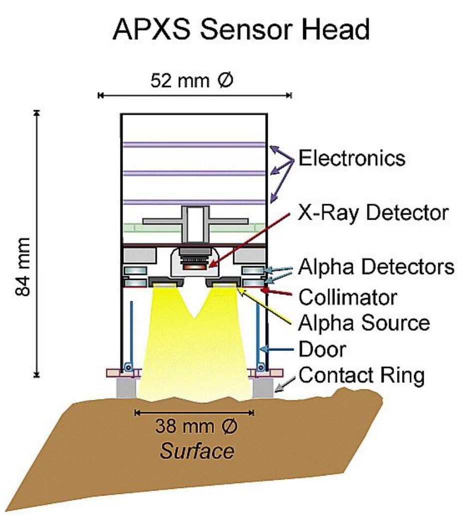
Parameter	Value
Length, mm	90
Diameter, mm	53
Mass, g	250
Power +12 V, mA	27
Power −12 V, mA	25

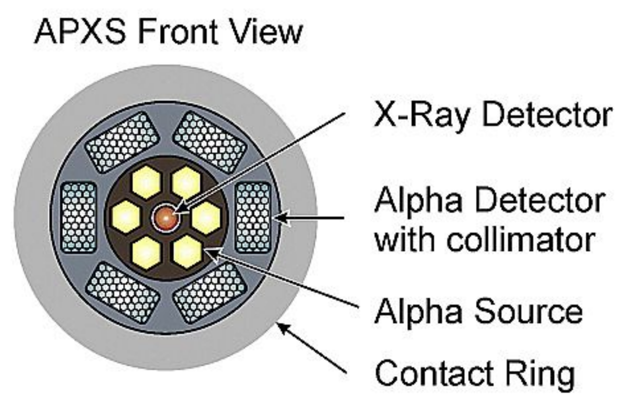
Table 1, depicting specifications for the APXS Sensor Head.
Source (above): (Rieder et al., 2003)

Table 2. APXS Main Electronics

Parameter	Value
Length, mm	170
Width, mm	100
Height, mm	10
Mass, g	120
Power +5 V, mA	60
Power −5 V, mA	40

Table 2, depicting specifications for the APXS Main Electronics.
Source (above): (Rieder et al., 2003)





Source (above): (Rieder et al., 2003)

Communications System

The communications system contains the MST that will transmit to the communication package nearby. The transponder is hooked up to a Centaur computer, which will control the processes, protocols, and scripts. When new data is collected from the instruments (or it sends a digital acknowledgement from the respective dataline or protocol), the computer can activate the protocol to tell the transponder to send the data to the communication package, which will then transfer the data to Earth. In regards to some instruments using the RS232, a converter can be used to translate the computer's RS422 to the appropriate RS232 to RS422 converter.

4.1.3. Precision of Instrumentation, Repeatability of Measurement, and recovery System

DAN Precision and Accuracy
For measurements that are less than two minutes long, the hydrogen distribution accuracy by weight is ~1%. For measurements of about thirty minutes, the accuracy, by weight, is .1% to .3%(*DAN Instrument Information – MSL – Mars Science Laboratory*, n.d.-b). The resolution (precision) of how DAN detects the depth and distribution of H- and OH- molecules is less than 1 meter for vertical measurements and .5 to 100m horizontally(*pds-geosciences.wustl.edu*, n.d.-a).

DAN Recovery System
For the DAN, the collected data is temporarily stored in the DAN Detector and Electronic (DE) section. It is then sent to the main lander computer every 20 seconds at a maximum rate of 4 KB/sec. The computer then communicates with the transponder, and data is sent back to Earth. (Litvak et al., 2008)

APXS Precision and Accuracy (Gellert, n.d.-b)
The APXS has an accuracy of ~10%. The best spectral resolution that can be achieved is <150 eV.

APXS Recovery System
For the APXS, the data is stored in a 32 kilobyte SRAM in the main electronics component, and is transferred via RS 422 link to the lander's main computer. It is then transmitted to the transponder and then back to Earth(Rieder et al., 2003).

TECP Precision and Accuracy(Zent et al., 2009):
The TECP has an accuracy of 10%, a 2 K precision for temperature, and a .005 precision value for dielectric permittivity.

TECP Recovery System

For the TECP, data is sent directly to the lander's computer via RS232 link, which is then transmitted to the transponder and then back to Earth(Hecht, M., 2020).

4.1.4. Validation and Verification Plan

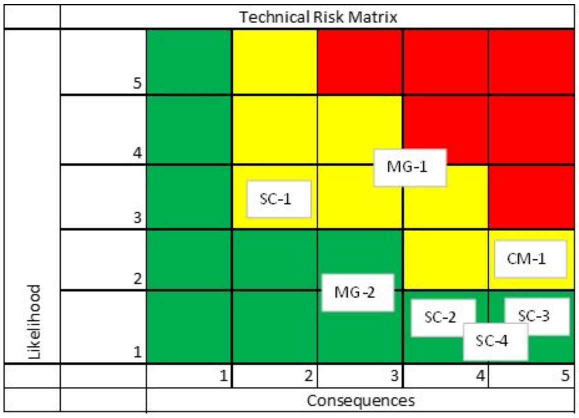
Instruments will be tested throughout the whole process for workability by checking if it gives the correct output. The last few weeks before launch, extra care will be taken to make sure that the instruments function properly. On board the payload, there will be a Centaur computer which will essentially be the "brain" of the processes. To confirm if an instrument is running, the computer will check the data line to see if it is a digital '1' or '0.' For transponder verification, it may use RS422 communications to verify communication and other factors, or Tx/ Rx pins. If there is an acknowledgment ("ACK") bit sent by the transponder after a request is sent out by the computer, that means that the transponder is working and is able to communicate with the computer.

4.1.5. FMEA and Risk Mitigation

Scientific Instruments FMEA And Risk Mitigation Chart										
Function	Failure Mode	Effect	Sev	Cause	Occ	Design Controls (prevention)	Design Controls (Detection)	Det	RPN	Recommended Action
Collect data about the content of the surface of the surroundings of the lander	Instruments measure irrelevant content (i.e. the lander itself or thruster material)	Data will be vague and muddled	7	Instruments and systems are not embedded within PIE-L in a way that they do not interfere with each other	8	Assembly of instruments will consider affect of other instruments and systems, design robot arm to be long enough to reach past effects of thrusters on surface	Measure data that consistently shows up when running configuration in various ways - delete data as "noise"	2	112	Research on noise mitigation recommended
	Unexpected electrical energy from surface	may cause instruments to short	8	Electrical activity on the lunar surface not previously anticipated	3	insulating nesting for instruments	not easy to detect or know if this was a real problem	1	24	Electrically insulated equipment, including backup systems that turn on only after landing
	Instruments stop working	Mission is a failure	10	Extreme cold or heat	6	thermal nesting for instruments	literature on instruments must state that instruments can work in severely fluctuating temperatures	1	60	
Relay data to Earth's surface	Data is incomprehensible	Scientists are unable to ascertain if there is water present at landing site	10	Instruments lose calibration	5		Instruments are tested on a regular basis for stability and reliability	2	100	
	Data does not arrive	Mission is a failure	10	Transponder not working	6	Use a transponder design that is tried and true	Test transponder in extreme environements at long distances	4	240	

Other mission critical FMEA and Risk Mitigation chart										
Success Criteria	Failure Mode	Effect	Sev	Cause	Occ	Design Controls (prevention)	Design Controls (Detection)	Det	RPN	Recommended Action
The lander is ready for its launch window	Project is severely behind schedule	The project is not well-tested with some areas still left as as accepted risks	7	Team 7pi members are too busy to complete phases of the project on time	8	Keep track of sources, maintain google drive with all docs for research well-organized	Constant checking in with team members	3	168	After completing PDR, perform a maintainance on the google drive and leave appropriate contact information for the original members of Team 7pi
PIE-L is within 10 percent of its proposed budget	The project is severely over budget	The project is delayed or perhaps cancelled	9	Manufacturing, testing methods are wasteful, unforeseen personell expenditures	7	Maintain strict budget - major decisions are to involve budget approval	Frequent meetings with budget and logistics team to ascertain viability of current plan	3	189	Consider seeking professional/experienced budgeting expertise

Legend	
SEV	Potential Severity
OCC	Likelihood of Occurrence
DET	Probability of Detecting and Avoiding
RPN	Risk Priority Number (SEV * OCC * DET)



Trend	Rank	Risk ID	Approach	Risk Title
o	1	CM-1	M	Transponder does not work
o	2	MG-1	R	Project is severely over budget
^	3	MG-2	M	Project is severely behind schedule
o	4	SC-1	M	Data collects irrelevant content
o	5	SC-2	W	Data is impossible to interpret
o	6	SC-3	A	Instruments break due to temperature
o	7	SC-4	A	Instruments experience unexpected electrical surge

Legend		
Risk ID	Trend	Approach
SC - Science	^ Up	M - Mitigate
CM - Communication	v Down	W - Watch
MG - Managent	o unchanged	A - Accept
		R - Research

Given the event occurs, what is the magnitude of the impact to the PIE-L Program?						
	Level	1	2	3	4	5
	Technical	Minimal or no impact	Mod. Reduction, same approach retained	Mod. Reduction, but workaraounds avail	Major reduction, but workarounds available	Unacceptable, No alternatices exist
	Schedule	Minimal or no impact	Additiona; Activities required, able to met need dates	level 2 milestone slip of around 1 month	Level 2 milestone slip of over a month, or program critical path impacted	Cannot achieve Major Program Milestone
Consequences	Cost	Minimal or no impact	Individual system budget increase of less than 5%	individual system budget increase between 5 and 10 percent or program budget increase of 2 percent	individual System Budget increase of over 10 percent or pgram budget increase of over 5 percent	Individual System Budget Increase of over 15 percent or Program Budget increase of over 10 percent

	What is the likelihood the situation or circumstance will happen?			
	Level	Probability	Probability (Safety)	...or - the current process...
	5	Near Certain 80%-100%	Likely to occur immediately	cannot prevent thiis event, no alternate approaches or processes are available
	4	Highly Likely 60%-80%	Probably will occur in time	cannot prevent this event, but a different approach or process might
	3	Likely 40%-60%	May occur in time	may prevent this event, but additional actions will be required.
	2	Low Likelihood 20%-40%	Unlikely to occur	is usually sufficient to prevent this type of event
Probability	1	Not Likely 0% - 20%	Improbable to occur	is sufficient to prevent this event

The team is using the above methods to track risks in the technical and administrative arenas. Risks are analysed based on mission success criteria and ranked by the FMEA and Risk Matrix chart. As shown above, according to the risk analysis, the greatest threat to the project is the project going over its intended budget.

Thorough explanation of risks

Risk SC-1 - Data collects irrelevant content - The causes of this risk may be that the scientific instruments are not calibrated to read data from surroundings correctly, or perhaps that the team has not mitigated the noise due to residue from the thruster fuel used for landing. There is a known chance that TECP might not calibrate correctly due to dust being on the calibration plate. This risk has medium consequences. There are probably many past missions where this risk was present that have successfully mitigated it, therefore the team believes that by studying what was done before in terms of noise reduction, the team will most likely be able to sort out what data is relevant.

Risk SC-2 - Data is impossible to interpret - The cause of this risk is that the instruments lose their calibration due to an unexpected electromagnetic interference or perhaps that the robot arm upon which the instruments are mounted behaves unexpectedly. While devastating to the mission, these risks do not seem likely. The team has not looked into shielding against electromagnetic or other disasters Therefore this risk will be watched.

Risk SC-3 - Instruments break due to temperature - PIE-L is going into areas of both extreme heat and extreme cold, and therefore any of its systems will be sensitive to fluctuations in temperature. Should any of the scientific equipment cease to work during the mission, it may lead to mission failure. However, the instruments used in this project are flight tested and tested in extreme temperatures. Therefore this is an accepted risk.

Risk SC-4 - Instruments experience unexpected electrical surge - In the same vein as risk SC-2, the instruments may be flight tested, but no one can know every danger facing them on the planet - perhaps there may be some electromagnetic charge on the lunar surface heretofore unknown. Since it is impossible to know, the risk will be accepted, even though the consequence is high.

Risk CM-1 - Transponder does not work - any of the risks to the instruments could apply to the transponder. If the transponder does not work, the mission will be a failure, so the risk will have to be mitigated through rigorous testing and research into past successful transponders.

Risk MG-1 - Project is severely over budget - Since the team is looking into researching a smaller, more lightweight version of one of its chosen scientific instruments, DAN, as well as not knowing for sure the amount of redesigning and testing PIE-L must endure, this risk is great. That is why the recommended action to mitigate this risk is, going into the CDR phase, hiring a new team member whose specialty is budget for science instruments and projects such as these.

Risk MG-2 - Project is severely behind schedule - Since the team presumes the lander must be on time for its flight window of October 16th 2021 or else the mission fails, it is of high consequence to both the whole project and the budget that the mission is on time. However, since the launch date is so far away the project has enough slack so that a change in schedule at this juncture would not be of huge consequence. The likelihood that schedule will change so drastically as to be late for launch is low given the mitigation that personnel will be reevaluated for time and commitment to the project and the Google Drive will have sufficient hand over materials should any person decide to leave the project.

4.1.6. Performance Characteristics

Each of the science instruments selected has flown on missions to Mars or beyond before. Mars is, on average, about -60 C, and can get as cold as -125 C at the poles. As later described in 5.2.1, Shackleton Crater can get as cold as 90 Kelvin, or -183.15 C, which is similar to Mars' pole temperatures. Mars, like the moon, has rocks and regolith on the ground. Since these are the two main hazards that the science instruments face on the moon, the team chose instruments that have withstood Martian conditions before.

The TECP successfully collected data as a part of the Phoenix lander, which went to Mars' northern arctic plain(Administrator, 2015).

The DAN flew on Curiosity which went to Mars' Gale Crater (temperature ranges from -90C to 0C)(Gov, n.d.). To the best of the team's knowledge, the only instrument which has trouble functioning at extremely low temperatures is the DAN, which cannot survive at below -55 C and cannot take data at below -40 C. However, due to the lander's comprehensive heating system, keeping DAN and the rest of the lander at functioning temperatures is possible.

The APXS has flown on missions such as Pathfinder, both of the Mars Exploration Rovers, and Curiosity, demonstrating that it is tried, tested, and true technology that has handled a wide variety of conditions successfully(Gellert, n.d.-a; *Water on the Moon: Direct evidence from Chandrayaan-1's Moon Impact Probe*, n.d.).

4.2. Science Value

4.2.1. Science Payload Objectives

The mission's science objectives are to:
1) Verify the existence of water.
2) Collect data on the depth and distribution of water.
3) Collect data on the elemental distribution of the crater floor.

Reasoning and Purpose of Data for #1: Water Verification
The reasoning for choosing science objective #1 is simple: there has not yet been a lunar lander to physically sample and confirm the presence of water on the moon. Although several orbiting missions have strongly suggested water presence on the moon, there has not yet been true verification, regardless of however little doubts about lunar water presence there may be left.

The data from this science objective (fulfilled by the TECP and the DAN), regardless of whether water is found or not, will tell scientists about whether their predictions of water existence at the bottom of Shackleton and other craters is correct. Essentially, it can either confirm good science, or encourage better science by revealing previous flaws. And, the data can provide some context to the data that previous water-searching orbiters detected.

Reasoning and Purpose of Data for #2: Depth and Distribution of H- and OH-
The team's reasoning for choosing science objective #2 is as follows: in order to understand lunar water ice, and whether it is usable, scientists must have data on how much water exists, and how it is distributed.

This data can be used by both scientists and explorers. For example, if only a tiny amount is found, that could signify to scientists that the moon formed or obtained its water under certain conditions. That same tiny amount found could mean that future manned missions cannot rely on using lunar water as a resource, and that they must account for bringing their own water along. Or, if the water tends to be distributed very evenly, that could also indicate conditions of lunar formation, and provide confirmation to explorers that water will be easy to find.

Reasoning and Purpose of Data for #3: Elemental Distribution of Crater Floor
The team's reasoning for choosing science objective #3 is both scientific and functional. The team wanted to choose objectives that have value to both lunar scientists and

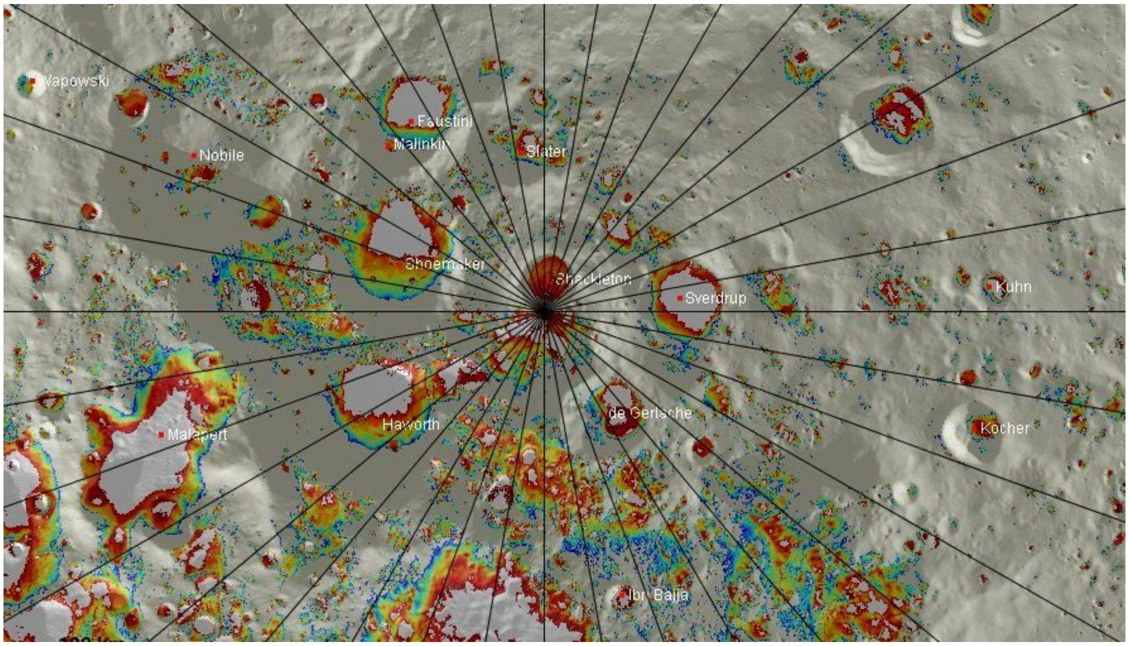
future lunar explorers, and for the objectives to go together. Now that objectives #1 and #2 have established the existence and location of water, a follow up question that the team had was: what is near the water? That is where objective #3 — determining the elemental distribution — comes in.

The data on the elemental distribution of the crater floor — or, simply put, what kinds of elements exist and in what amounts on the crater floor — provide never before seen information about what the top layer of the bottom of a crater looks like. Although previous missions have crashed into the moon to observe its composition, such as the Moon Impact Probe which landed ballistically near Shackleton Crater, there has never been a lunar lander sent to study the bottom of a crater(*Water on the Moon: Direct evidence from Chandrayaan-1's Moon Impact Probe*, n.d.). Furthermore, it is in the interest of scientists to determine if there are certain elements that are often present near water reserves because this information could provide the science community a better understanding of how the moon formed and how it obtained its water. This data is also in the interest of the space exploration community — the potential correlation between elemental distribution and water ice reserves could provide the space exploration community guidance on where lunar water reserves are likely to be found and what kind of filtration they might need, which is key information in order for future missions to the moon to utilize lunar water ice reserves. The data collected from the APXS for the purpose of this science objective therefore goes hand in hand with the data that comes from DAN (science objective #2), which tells us the depth and distribution of water. The main purpose of this science objective, for the sake of both scientists and explorers, is for elemental distribution to be compared with water ice deposit locations to determine if there is a correlation between elemental composition of the crater floor and water ice abundance, and if the elemental composition of the crater floor has any implications for the usability of the nearby water ice.

4.2.2. Creativity/Originality and Uniqueness/Significance

We ultimately ended up choosing Shackleton crater as our landing site. We made this decision based off the following factors:

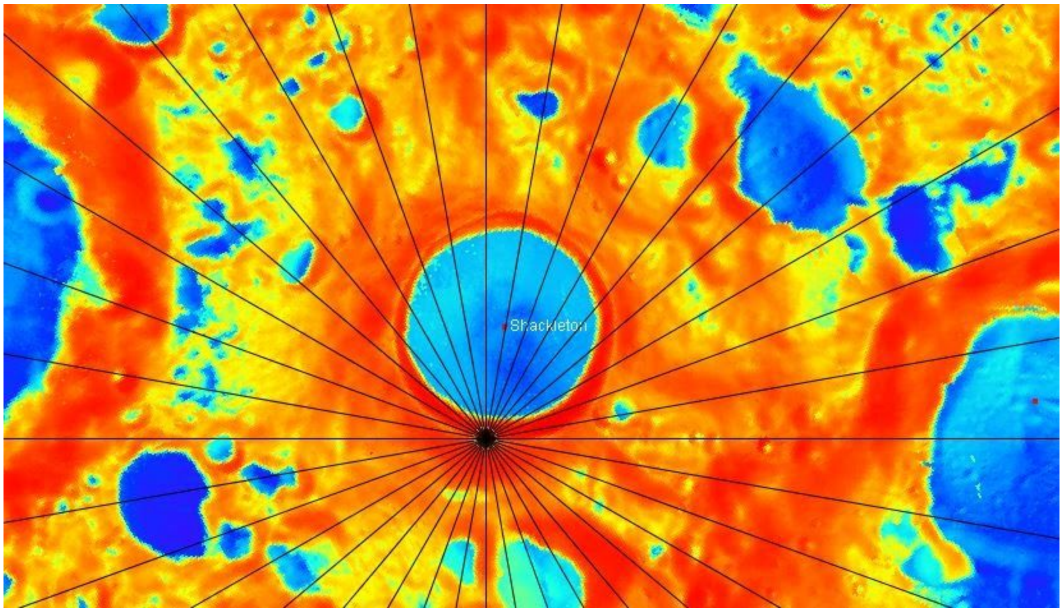
1) **Previous satellite data indicating potential of water presence.** Shackleton has the most data available for water ice as well as the highest values.

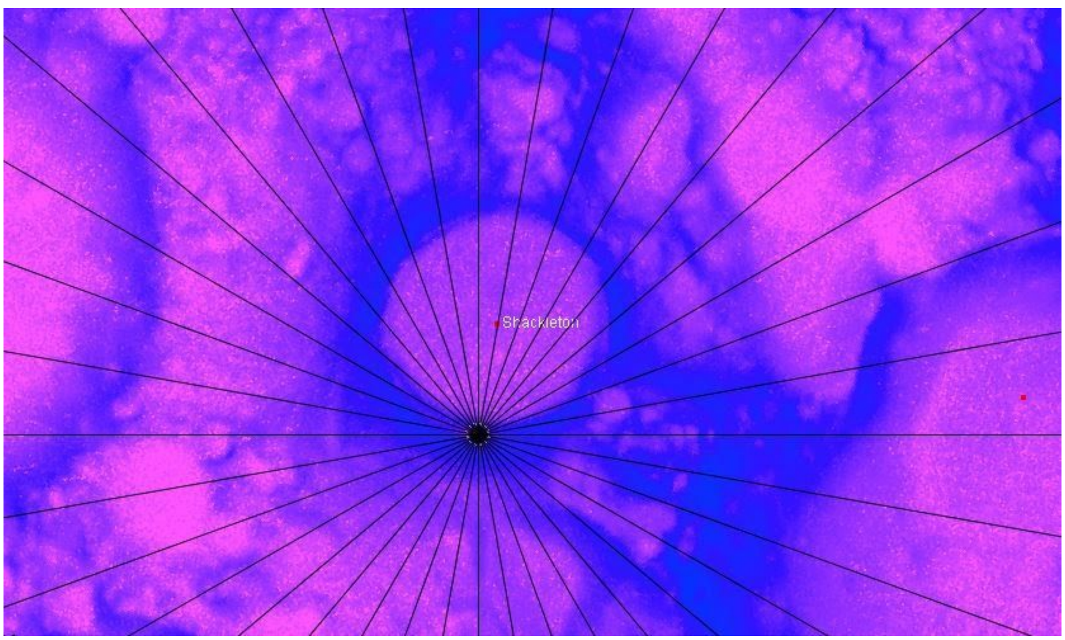


Data is presented on a RGB scale - Diviner South Pole Ice Depth Stability

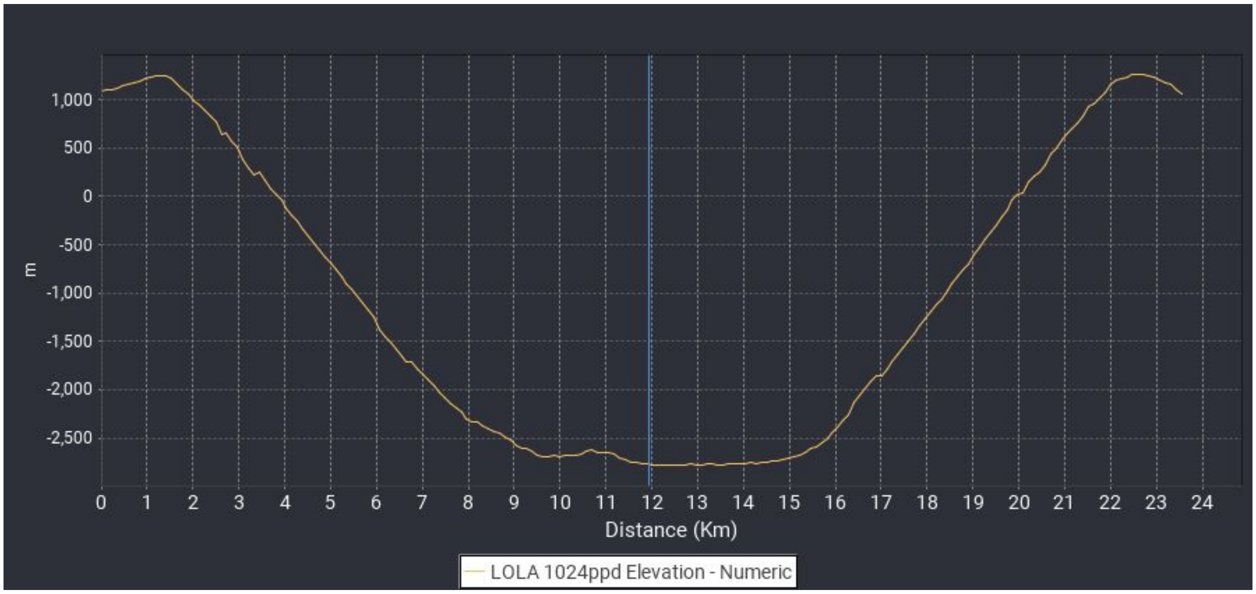
Previous studies of Shackleton crater have shown a lack of large sheets of relatively pure water ice (*Lack of Exposed Ice Inside Lunar South Pole Shackleton Crater*, n.d.). However, PIE-L will be testing the percentage and possibility of water ice being mixed with other minerals within lunar regolith.

2) **Cold enough temperatures to support water ice year round.** These images show the maximum and minimum temperatures for Shackleton respectively. Throughout the year it is cold enough to support water ice.





3) **Landing feasibility.** Shackleton consists of sides that slope steeply towards a bottom that flattens out and then has a hill in the center. This flat section near the edges that slope to the top provides a suitable place for PIE-L to land. This location would provide regolith from the sloping sides for the instruments to test and a flat enough surface for PIE-L to have a suitable landing.



4) **Uniqueness.** Shackleton provides a rare opportunity where there is an environment suitable for the retention of water ice on the inside of the crater. However, on the rim there are locations that receive a majority of sunlight throughout the year(*On the Rim! | Lunar Reconnaissance Orbiter Camera*, n.d.). This provides an opportunity for access to possible water ice within the crater and a source of solar power from the large amounts of sunlight on the rim for our communications team and possible future missions. PIE-L will be the first mission to land inside a crater with possible water ice providing valuable information to future missions and bases on the moon. Shackleton is also known as an “unusually well preserved ancient crater” which would provide the opportunity for future geological missions to study the history of the moon(*Detailed Characterization of Shackleton Crater*, n.d.).

4.2.3. Payload Success Criteria

As defined in 1.2.1, the science objectives are as follows:

1. Verify the existence of water.
2. Collect data on the depth and distribution of water.
3. Collect data on the elemental distribution of the crater floor.

Therefore, since each instrument mainly corresponds to each objective, here are the payload success criteria:

Baseline Criteria

- The existence of water is either confirmed or denied in the landing site through valid data that is successfully transmitted to Earth.

Threshold Criteria
- The existence of water is either confirmed or denied in the landing site through valid data that is successfully transmitted to Earth.
- The depth and distribution (or lack thereof) of H- and OH- is detected through valid data that is successfully transmitted to Earth.

Surpassing Criteria
- The existence of water is either confirmed or denied in the landing site through valid data that is successfully transmitted to Earth.
- The depth and distribution (or lack thereof) of H- and OH- is detected through valid data that is successfully transmitted to Earth.
- The elements that exist on the crater floor are detected through valid data that is successfully transmitted to Earth.

The criteria are closely tied with the science objectives (1, 2, and 3), which increase in value in order.

Method for Answering Deliverables:
- Although some instruments can contribute to multiple objectives, the TECP meets objective #1, the DAN meets objective #2, and the APXS meets objective #3
- Instruments are integrated with lander so that they have maximum reach in order to collect as much data as possible
- Instruments are appropriately powered via a lithium-sulfur battery
- Instruments are protected from becoming too cold via a loop heat pipe system and kapton layering
- Data for each instrument is stored and transmitted via the lander's central computer

4.2.4. Describe Experimental Logic, approach, and method of investigation

Method of design:

The mission's science objectives are as follows:
1) Verify the existence of water.
2) Collect data on the depth and distribution of water.

3) Collect data on the elemental distribution of the crater floor.

Data is collected from the Thermal and Electrical Conductivity Probe (TECP); the Dynamic Albedo of Neutrons (DAN), and the Alpha particle X-Ray Spectrometer (APXS).

In order to successfully collect data, the TECP and the APXS are mounted on the end of a robotic arm, while the DAN is towards the base of the arm. This allows for a greater range of motion, which allows for more data collection. Each instrument is wired to its own set of electronics (which come with the instrument) that allow for data to be stored and then sent to the main lander computer for transmission to the transponder.

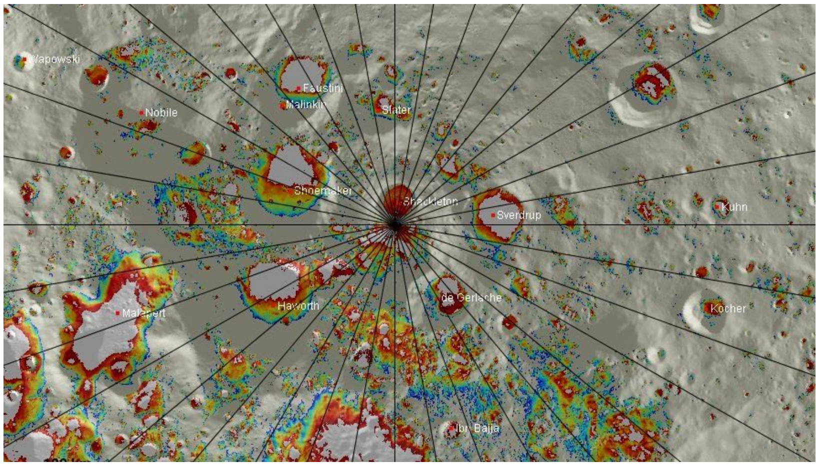
To maintain instrument functionality, each instrument is connected to the main lander battery for power, which is expected to last at least 1 month. Each instrument is connected to the main lander heat source via tubes that run heated fluid inside from the main lander heater to the instruments. Each instrument is also well-protected by the lander during descent.

Importance/Significance of Landing Site

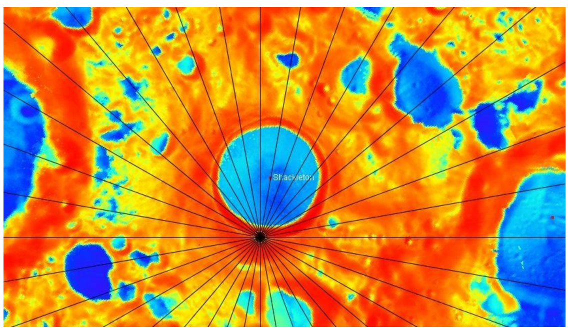
As mentioned in 4.2.2, the criteria that we used for selecting the landing site was as follows

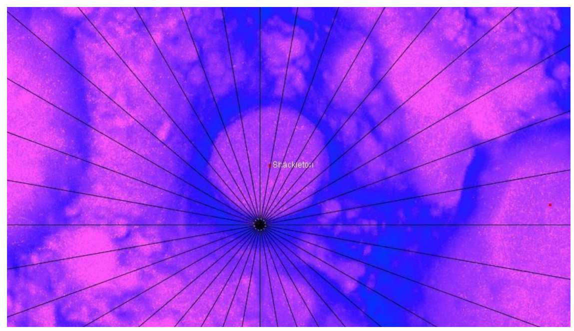
1. Previous satellite data indicating potential of water presence.
2. Cold enough temperatures to support water ice year round.
3. Landing feasibility.
4. Uniqueness.

As discussed in 4.2.2, the Diviner South Pole Ice Depth Stability filter shows that #1 is met.

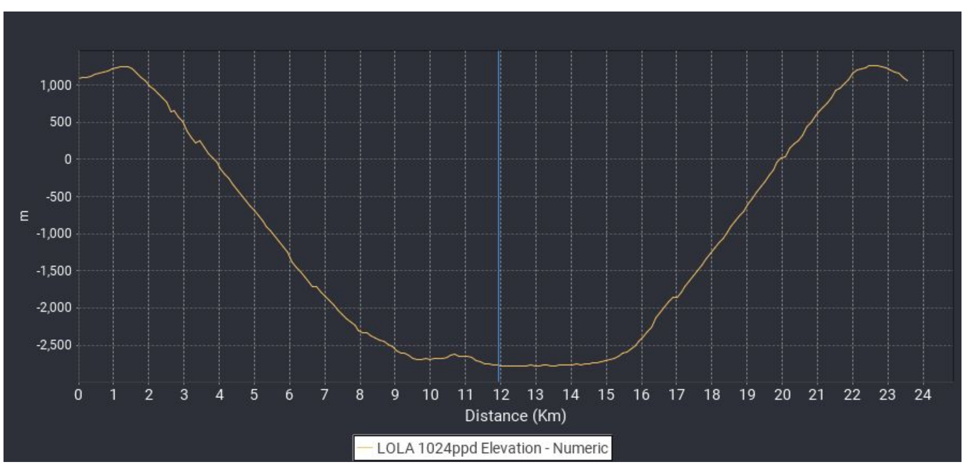


As discussed in 4.2.2, the Diviner Summer Max Temperature - Poles and Diviner Winter Minimum Temperature - Poles filters show that #2 is met.

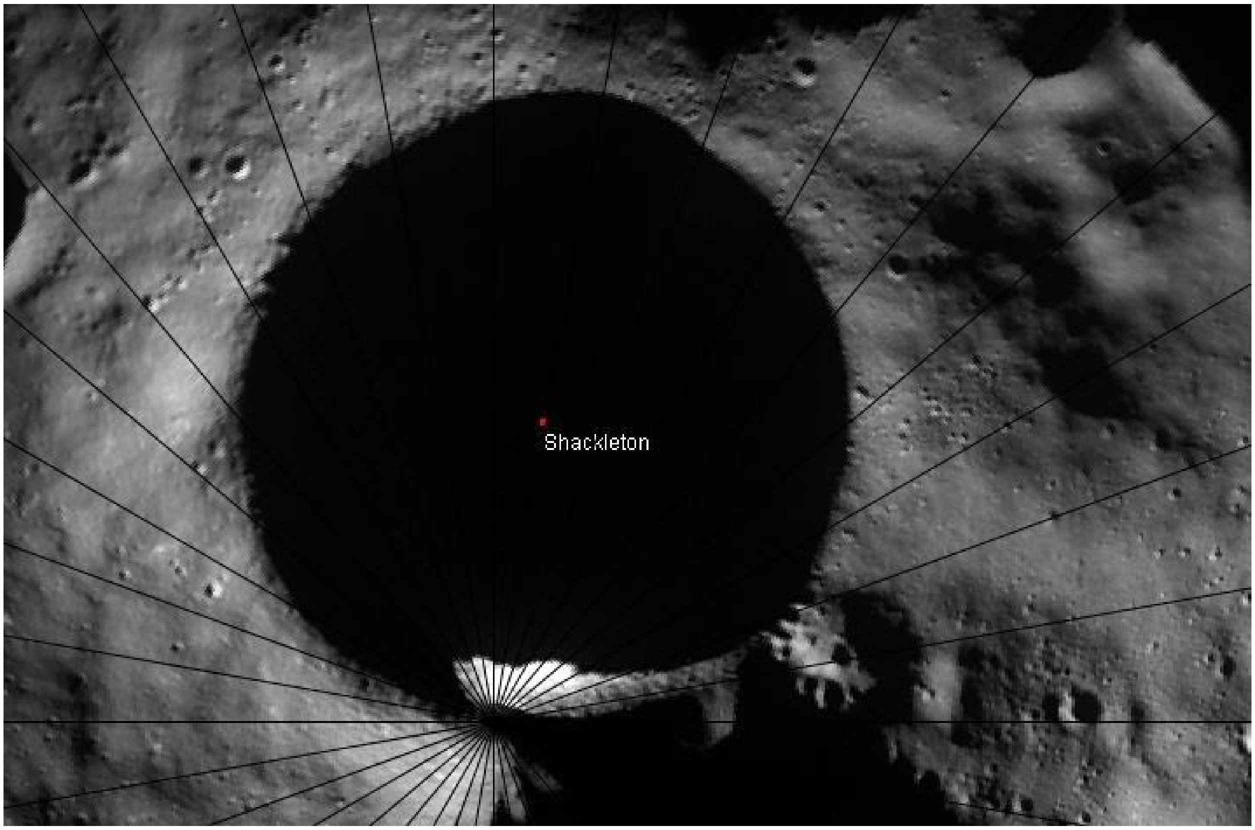




As discussed in 4.2.2, a cross section of Shackleton Crater using LOLA 1024ppd Elevation - Numeric data set shows that that #3 is met due to the wide flat area (~6-7 km) at the bottom, ensuring that the lander has a flat place to land.



As discussed in 4.2.2, #4 is met due to the unique opportunities for science that landing in Shackleton provides and illustrated in the image below. The bright portion on the southern edge of Shackleton Craters rim receives sunlight for 90% of the year as surmised through the links given in 4.2.2.

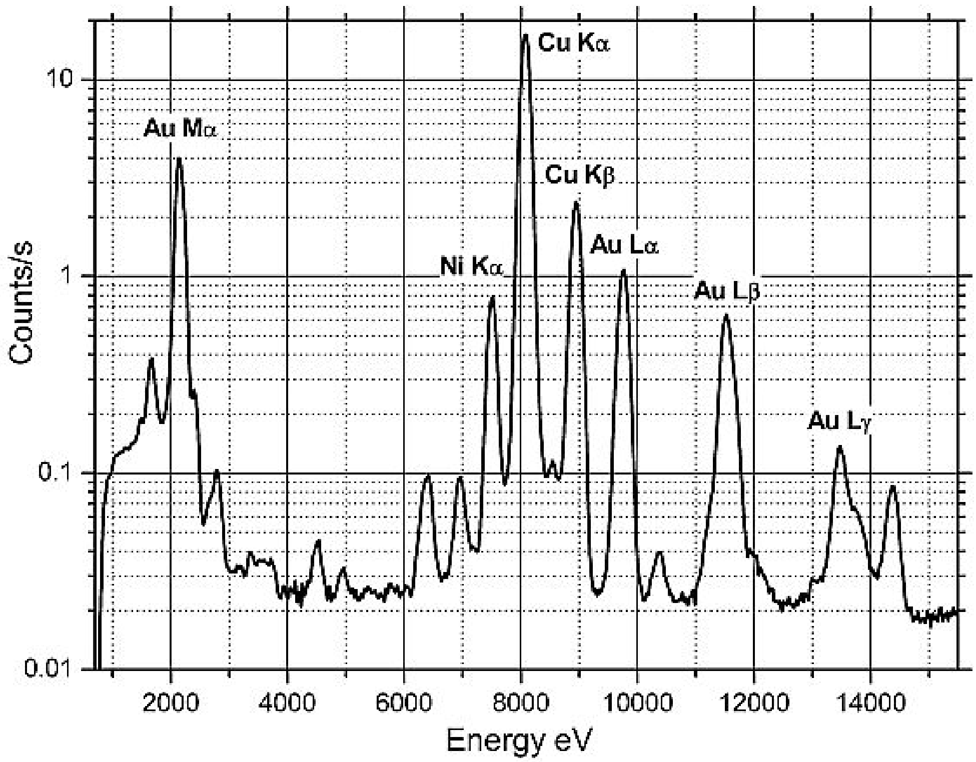


4.2.5. Describe Testing and Measurements, including variables and controls

AXPS Calibration *(Rieder et al., 2003)*

The AXPS instrument has a built-in system for calibration. The doors that cover the sensor to protect it have gold, carbon, and nickel layered on the inside part of the copper-beryllium doors. The gold and carbon are used to calibrate the energy and efficiency in the alpha spectrum, while the copper and gold are used in the X-ray spectrum to calibrate energy, full width at half maximum (resolution), and linearity (proportionality of a change in a measured variable to the change in instrument output). The gold is also used in X-ray mode to help detect contaminations of the beryllium window that protects the detector. The values detected for these calibrations on the moon will be compared to those on Earth, so the instrument can be calibrated accordingly. The calibration procedures that will occur on Earth will be the same as on the moon, except that they will take place in a near-vacuum to simulate the lack of atmosphere. In summary, the control variables are the gold, carbon, nickel, and copper on the calibration target, and the data collected from the target on the moon will be calibrated using data taken before launch.

Here is an example of X-Ray spectra taken using the internal calibration target:



DAN Calibration*(DAN PDS Data processing flow, n.d.)*

In order to calibrate the DAN after it has landed on the moon, the team will use the calibration method for the DAN that was included on Mars Science Laboratory. The DAN's data is normalized after it is collected — there is no prior calibration before the data is collected. DAN collects both "active" and "passive" data, and both are normalized differently. In order to normalize the passive data, two datasets that are at least 1200 seconds apart are chosen. Then, the data — an example of which is shown in 4.2.6 — undergoes normalization according to the following equations:

$$C_{eff\_corrected}(t) = C(t) / A_{norm}$$

where

$$A_{norm} = \left(1 - e^{-a1(t-a2)}\right)$$

CTN detector: a1=11.985331, a2=-0.17908154
CETN detector: a1=3.7732457, a2=-0.4379

C(t) – detector count rate in channels 3-14.

t – "Martian Julian day", where 1.0 corresponds to a duration of 1 sol.

In the data, the variable "CTN_BKGD" is set to 30,72, and "CETN_BKGD" is set to 13,73.

The active data is also normalized, using the following recommendations:

Background is calculated as: $C / PulsNum / BgdTime$, where C – total counts in channels [3:14] of all background bins, PulsNum – number of pulses during current frame, BgdTime – the length of background bins (in sec).
The background is equal for all 64 items of the BKGD array
The COUNTS array is filled with the sum of counts in channels [3:14], for channels [0:61]. Channels 62 and 63 are discarded.
The above statements are true for both, CTN and CETN arrays.

Background CTN and CETN Counts are adjusted as follows:(Jun et al., 2013)

$$C_{\text{corrected}}(t) = C_{\text{measured}}(t) \Big/ \left(1 - e^{-k(t-t_0)}\right),$$

For more information on the calibration of DAN, visit the [Russian Academy of Sciences Space Institute Research's Dan PDS Data Processing Flow]().

TECP Calibration(pds-geosciences.wustl.edu, n.d.-b)

For most of the TECP's sensors, on-Earth calibrations were made to determine calibration functions that link a sensor to another variable. The on-Earth calibrations and the calibration functions are discussed.

Board (temperature sensor) Calibration — Part 1:
On Earth, an Engineering Model (EM) unit will be used to find the temperature difference between the board temperature and the temperature on the aluminum cover directly above the board temperature sensor. The TECP was then heated up externally and a function of the temperature between the PCB inside the TECP and the outside of the TECP's cover was determined. The derived equation defines the relationship between the PCB and the outside of the TECP. This equation is used to calibrate the board temperature sensor on the TECP once it is on the surface.

Thermocouple (temperature sensor) Calibration:
A thermocouple is a temperature sensor that is composed of two different wires that are welded together, with a voltage created in the junction between the wires when there is a temperature difference. During thermocouple calibration, the measure of magnitude of induced voltage due to temperature difference across the thermocouple (called the Seebeck Coefficient) versus temperature for the thermocouple alloys used in the TECP needles was determined. This coefficient determines the temperature difference between the needles of the TECP and the internal board temperature. This derived coefficient is then used to calibrate the thermocouple's data once it is on the moon in relation to the board temperature.

Dielectric Sensor Calibration:
To calibrate the dielectric aspect of the TECP, the dielectric sensor will be run in a near-vacuum on Earth that simulates the amount of atmosphere that the moon has. The same function will be run on the moon, with the TECP fully exposed to the lunar atmosphere. The values will be compared and the dielectric sensor's data will therefore be calibrated based on the difference between the dielectric values.

Electrical Conductivity Sensor Calibration & Thermal Properties Sensor Calibration:
To calibrate the electrical conductivity and thermal properties aspects of the TECP, on Earth, the TECP will be tested on five small, thin plates with known resistance. These small plates, composed of copper, gold, aluminum, macor (ceramic glass), and expanded polystyrene will then be attached to the lander. Upon landing, the TECP will be placed in contact with each plate and the electrical conductivity will be measured. Three plates are used to mitigate the possibility that lunar regolith interferes with the measurements — if any plate is drastically off of the expected value, while the others are at the expected value, then the outlier will be thrown out and not used for calibration. The values measured on the moon will be compared to the values measured on Earth. The electrical conductivity sensor will be calibrated based on those values.

Although the TECP has a humidity (H_2O vapor) sensor, since no such vapor can be found at freezing temperatures (such as those that exist at the bottom of lunar craters), that sensor will not be used, and therefore will not be calibrated.

For more information about the calibration of the TECP, please visit the TECP Calibration Report.

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

As mentioned in 4.1.3, the following are the limitations to the validity of data from the instruments*:*

DAN Precision and Accuracy
Accuracy: .1% to .3%.
Precision: <1m for vertical measurements and .5 to 100m horizontally.

APXS Precision and Accuracy
Accuracy: ~10%.
Precision: <150 eV.

TECP Precision and Accuracy
Precision: 2K for temperature, .005 precision value for dielectric permittivity
Accuracy: 10%

DAN Data Analysis(pds-geosciences.wustl.edu, n.d.-c)(pds-geosciences.wustl.edu, n.d.-d)

Derived Engineering Data:
This is general information about the conditions that DAN is in, such as time and temperature.

```
A = {DAN_RDR_DERIVED_ENG, $
           DAN_TIME          : 0UL, $                    Instrument time
           UTC               : BYTARR(23), $               UTC timestamp
           TEMP              : FLTARR(6), $                 Temperatures
           HV_LEVEL_CTN      : BYTE(0), $                      HV levels
           HV_LEVEL_CETN     : BYTE(0), $
           DSC_LEVEL_CTN     : BYTE(0), $                     DSC levels
           DSC_LEVEL_CETN    : BYTE(0), $
           LST               : BYTARR(8)}               Local Solar Time
```

Derived Passive:
The passive data set is data when the detectors are detecting, but the neutron generator is not pulsing. Essentially, it is to measure background noise.

```
A = {DAN_RDR_DERIVED_PASSIVE, $
          DAN_TIME          : 0UL, $                      Instrument time
          UTC               : BYTARR(23), $                UTC timestamp
          BEGIN_LAT         : 0.0, $              Measurement coordinates
          BEGIN_LON         : 0.0, $
          END_LAT           : 0.0, $
          END_LON           : 0.0, $
          COLL_DURAT        : 0.0, $            Collection duration  (sec)
          CTN_BKGD          : 0.0, $
          CTN_COUNTS        : 0.0, $
          CETN_BKGD         : 0.0, $
          CETN_COUNTS       : 0.0, $
          LST               : BYTARR(8)}
```

Derived Active:
The active data set is data when the detectors are detecting, but the neutron generator is not pulsing.

```
A = {DAN_RDR_DERIVED_ACTIVE, $
          DAN_TIME          : 0UL, $                      Instrument time
          UTC               : BYTARR(23), $                UTC timestamp
          LAT               : 0.0, $              Measurement coordinates
          LON               : 0.0, $
          COLL_DURAT        : 0UL, $           Collection duration (sec*10)
          NUM_PNG_PULSE     : 0UL, $          Number of pulses during frame
          PNG_FREQ          : BYTE(0), $               PNG frequency (hz)
          TIME_BIN_DURAT    : 0UL, $                   Always 999 (NaN)
          TIME_BIN_START    : FLTARR(64), $            Start of bin (msec)
          CTN_BKGD          : FLTARR(64), $
          CTN_COUNTS        : FLTARR(64), $
          CETN_BKGD         : FLTARR(64), $
          CETN_COUNTS       : FLTARR(64), $
          LST               : BYTARR(8)}
```

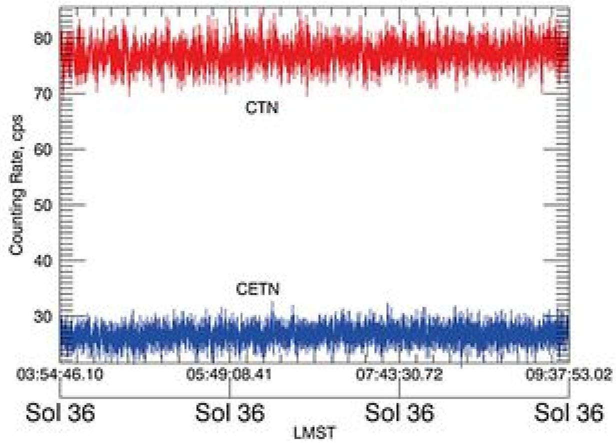
Averaged Passive:
This is the average of the Derived Passive data set during some time period, which is included in this data.

```
A = {DAN_RDR_AVERAGED_PASSIVE, $
          START_DAN_TIME     : 0UL, $                    Instrument time
          END_DAN_TIME       : 0UL, $
          START_UTC          : BYTARR(23), $             UTC timestamp
          END_UTC            : BYTARR(23), $
          BEGIN_LAT          : 0.0, $           Measurement coordinates
          BEGIN_LON          : 0.0, $
          END_LAT            : 0.0, $
          END_LON            : 0.0, $
          COLL_DURAT         : 0UL, $     Collection duration  (sec*10)
          CTN_AVG            : 0.0, $
          CTN_BKGD           : 0.0, $
          CTN_ERROR          : 0.0, $
          CTN_NORM           : 0.0, $
          CETN_AVG           : 0.0, $
          CETN_BKGD          : 0.0, $
          CETN_ERROR         : 0.0, $
          CETN_NORM          : 0.0, $
          START_LST          : BYTARR(8), $
          END_LST            : BYTARR(8)}
```

Averaged Active:
This is the average of the Derived Active data set during some time period, which is included in this data.

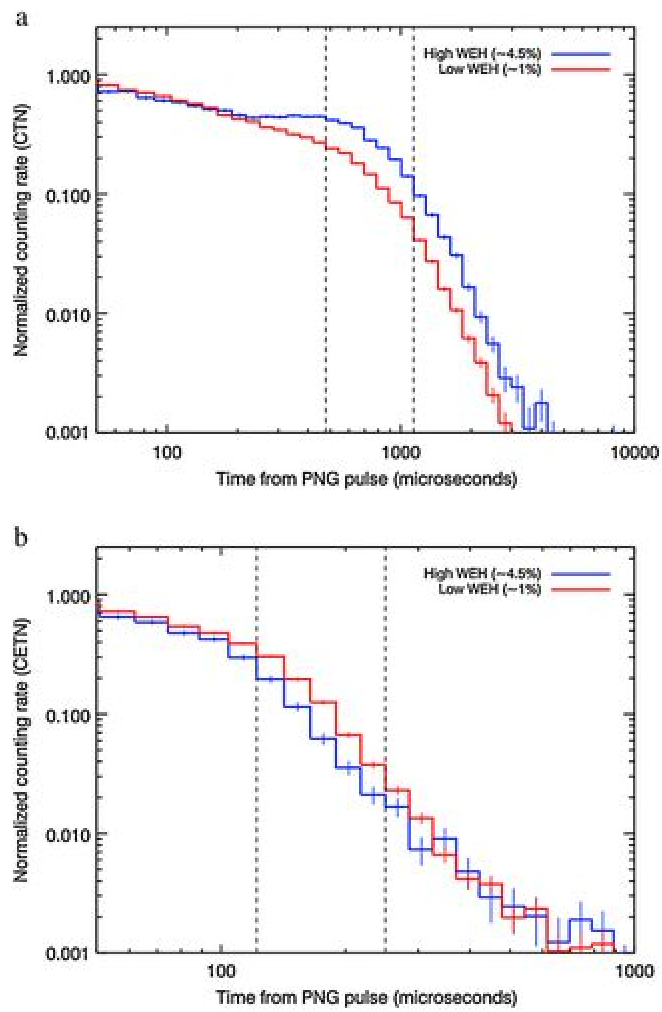
```
A = {DAN_RDR_AVERAGED_ACTIVE, $
          START_DAN_TIME     : 0UL, $                    Instrument time
          END_DAN_TIME       : 0UL, $
          START_UTC          : BYTARR(23), $             UTC timestamp
          END_UTC            : BYTARR(23), $
          BEGIN_LAT          : 0.0, $           Measurement coordinates
          BEGIN_LON          : 0.0, $
          END_LAT            : 0.0, $
          END_LON            : 0.0, $
          COLL_DURAT         : 0UL, $     Collection duration  (sec*10)
          NUM_PNG_PULSE      : 0UL, $
          PNG_FREQ           : BYTE(0), $
          TIME_BIN_DURAT     : 0.0, $

          TIME_BIN_START     : 0.0, $
          CTN_AVG            : 0.0, $
          CTN_BKGD           : 0.0, $
          CTN_ERROR          : 0.0, $
          CTN_NORM           : 0.0, $
          CETN_AVG           : 0.0, $
          CETN_BKGD          : 0.0, $
          CETN_ERROR         : 0.0, $
          CETN_NORM          : 0.0, $
          START_LST          : BYTARR(8), $
          END_LST            : BYTARR(8)}
```

Below is an example of passive data from DAN. This data represents background data that can then be subtracted from the active dataset.



Source: (Jun et al., 2013)

Below is an example of active data from DAN. Note that “WEH” stands for “Water Equivalent Hydrogen. The top graph is from thermal neutrons emitted after the DAN’s pulse, and the second is from epithermal neutrons emitted. The blue line shows high water content, while the red line shows low water content. The fact that the high water content line stretches further out along the x-axis while becoming lower on the y-axis in the first graph suggests that the may suggest that there is significantly less water close to the surface, since it took longer for those counts to hit the detector, and less of them hit the detector than those that came back quickly. The speed of counts returning can be analyzed to find depth of H.



Source: (I. G. Mitrofanov et al., 2014)

```
/* Identification Data Elements */
DATA_SET_ID                      = "MSL-M-APXS-4/5-RDR-V1.0"
PRODUCT_ID                       = "APA_402284882RSP00540043232_______P1"
PRODUCT_VERSION_ID               = "V1.0"
PRODUCT_TYPE                     = APXS_RSP
PRODUCT_CREATION_TIME            = 2013-03-12T21:00:00.000
RELEASE_ID                       = "0001"
SOURCE_PRODUCT_ID                = "APA_402284882ESC00540043232_______M1"
PRODUCER_FULL_NAME               = "RALF GELLERT"
PRODUCER_INSTITUTION_NAME        = "UNIVERSITY OF GUELPH"

MISSION_NAME                     = "MARS SCIENCE LABORATORY"
MISSION_PHASE_NAME               = "PRIMARY SURFACE MISSION"
INSTRUMENT_HOST_NAME             = "MARS SCIENCE LABORATORY"
INSTRUMENT_HOST_ID               = MSL
INSTRUMENT_NAME                  = "ALPHA PARTICLE X-RAY SPECTROMETER"
INSTRUMENT_ID                    = APXS
INSTRUMENT_TYPE                  = SPECTROMETER

PLANET_DAY_NUMBER               = 54
MSL:LOCAL_MEAN_SOLAR_TIME       = "Sol-00054M12:03:21:079"
LOCAL_TRUE_SOLAR_TIME           = "12:43:00"
OBSERVATION_ID                  = UNK
COMMAND_SEQUENCE_NUMBER         = 5
MSL:REQUEST_ID                  = "0"
ROVER_MOTION_COUNTER            = (4,3232,6,18,0,0,122,172,0,0)
ROVER_MOTION_COUNTER_NAME       = (SITE, DRIVE, POSE, ARM, CHIMRA,
                                  DRILL, RSM, HGA, DRT, IC)
SEQUENCE_ID                     = "apxs01010"
SEQUENCE_VERSION_ID             = "0"
MSL:ACTIVE_FLIGHT_STRING_ID     = A
SOLAR_LONGITUDE                 = -179.489
SPACECRAFT_CLOCK_CNT_PARTITION  = 1
SPACECRAFT_CLOCK_START_COUNT    = "0402284882.064"
SPACECRAFT_CLOCK_STOP_COUNT     = "0402284882.064"
START_TIME                      = 2012-09-30T13:50:58.635
STOP_TIME                       = 2012-09-30T17:32:18.631
TARGET_NAME                     = MARS
TARGET_TYPE                     = PLANET
```

Source: (*pds-geosciences.wustl.edu*, n.d.-e)

Table 1

X-RAY ENERGY	COUNTS
486.5	1800
510.9	0
535.2	0
559.6	0
584	0
608.4	0
632.8	557
657.2	605
681.5	582
705.9	618
730.3	601
754.7	532
779.1	484
803.5	515
827.8	541
852.2	529
876.6	559

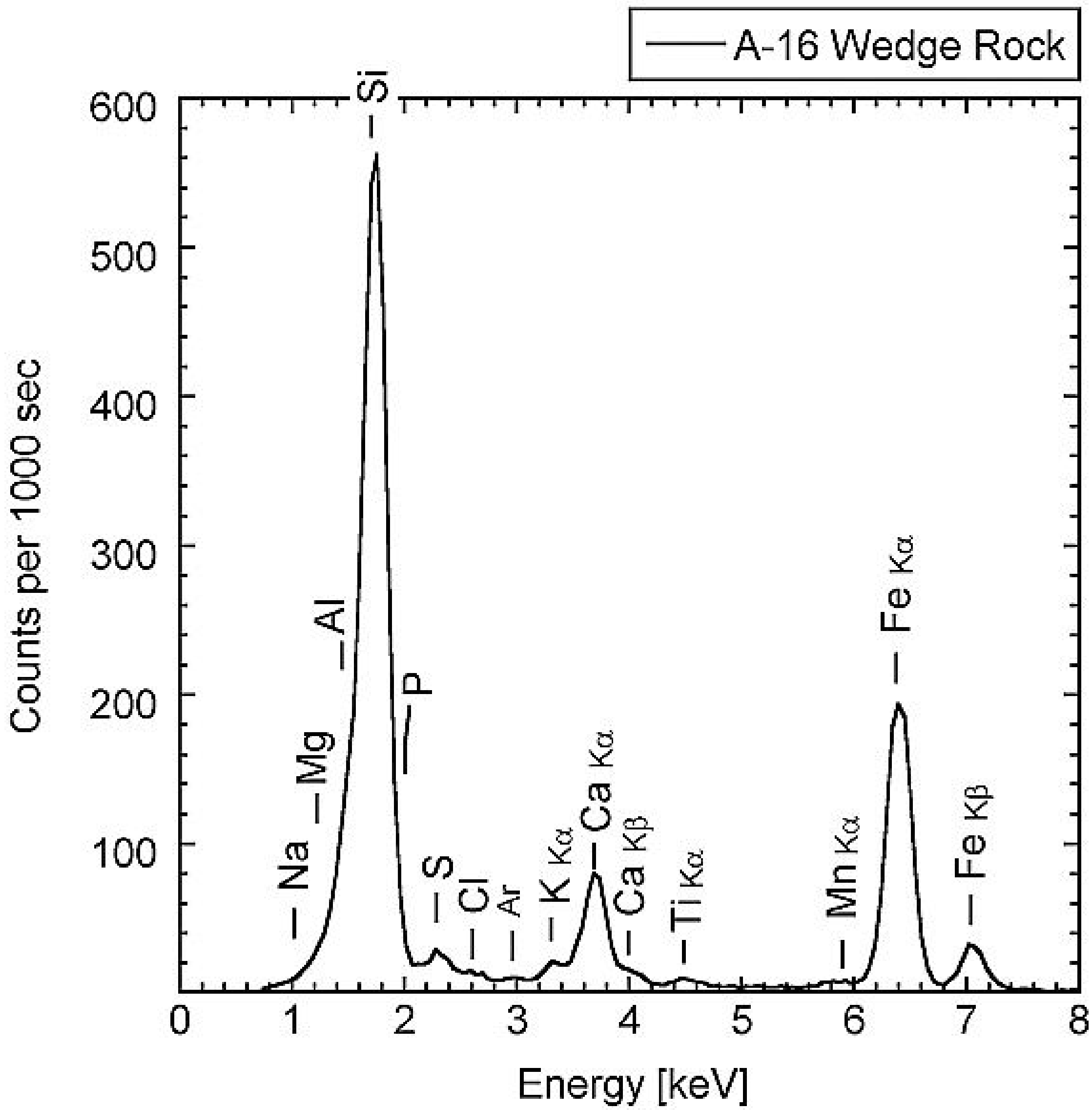
Source (above): (*pds-geosciences.wustl.edu - /msl/msl-m-apxs-4_5-rdr-v1/mslapx_1xxx/data/sol00054/*, n.d.)

Colum n #	Title	Byte s	Data Type	Units	Description
1	X-Ray Energy	10	ASCII_INTEGE R	N/A	Each record in the file represents an X-ray channel. The first field gives the

					energy in eV for that channel.
2	Counts	19	ASCII_INTEGER	N/A	Each record in the file represents an X-ray channel. The second field in the record gives the counts for that channel, with two exceptions. The value for the first channel is total counting time in seconds. The value for the last channel is the overflow, the counts observed at that energy and higher.

Source (above): (*pds-geosciences.wustl.edu*, n.d.-f)

The X-Ray Energy vs. Counts can be used to determine the composition of the sample. The amount of “counts” for a given energy level can then be analyzed using known values to determine chemical composition. An example graph of X-Ray Energy vs. Counts is below. Note the labels on the peaks, which indicate the type of element that created the peak.



Source: (Brückner et al., 2003)

TECP Data Analysis

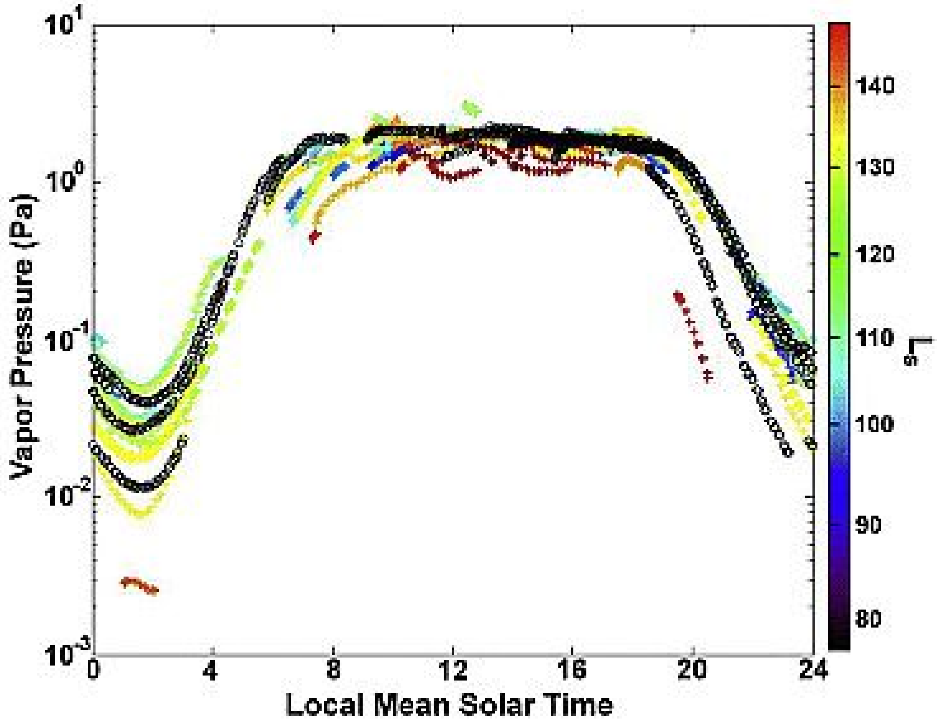
Phoenix TECP Data (Recalibrated, 2019)

1	15.06556	261.16	210.9166	0.7972439	0.2096851	931.677	0.3669305
1	15.06587	261.16	210.9166	0.7972439	0.2096851	931.677	0.3669305
1	15.06619	261.16	210.9166	0.7972439	0.2096851	931.677	0.3669305
1	15.0665	261.24	211.0082	0.8073854	0.2124155	943.529	0.3689281
1	15.06682	261.16	210.9166	0.7972439	0.2096851	931.677	0.3669305
1	15.06713	261.16	210.9166	0.7972439	0.2096851	931.677	0.3669305
1	15.06744	261.16	210.9166	0.7972439	0.2096851	931.677	0.3669305
1	15.06775	261.16	210.9166	0.7972439	0.2096851	931.677	0.3669305
1	15.06806	261.16	210.9166	0.7972439	0.2096851	931.677	0.3669305
1	15.06837	261.16	210.9166	0.7972439	0.2096851	931.677	0.3669305
1	15.06868	261.16	210.9166	0.7972439	0.2096851	931.677	0.3669305
1	15.06899	261.24	211.0082	0.8073854	0.2124155	943.529	0.3689281
1	15.0693	261.24	210.5171	0.7543508	0.1983693	881.551	0.3446944
1	15.06962	261.24	211.0082	0.8073854	0.2124155	943.529	0.3689281
1	15.06993	261.16	210.9166	0.7972439	0.2096851	931.677	0.3669305
1	15.07024	261.16	210.9166	0.7972439	0.2096851	931.677	0.3669305
1	15.07056	261.24	211.0082	0.8073854	0.2124155	943.529	0.3689281
1	15.07087	261.24	211.0082	0.8073854	0.2124155	943.529	0.3689281
1	15.07118	261.16	210.9166	0.7972439	0.2096851	931.677	0.3669305
1	15.0715	261.24	211.0082	0.8073854	0.2124155	943.529	0.3689281
1	15.07181	261.24	211.0082	0.8073854	0.2124155	943.529	0.3689281
1	15.07212	261.08	210.8088	0.7854431	0.2065161	917.887	0.364117
1	15.07243	261.16	210.9166	0.7972439	0.2096851	931.677	0.3669305

Example data from TECP instrument using its relative humidity sensor (above). This data was collected on the Mars Phoenix Mission and obtained via NASA’s PDS Geosciences Node. Title was added to data for clarity. The chart below describes the columns of the dataset(*pds-geosciences.wustl.edu*, n.d.-g)

Column #	Title	Data Type	Units	Description
1	Sol Number	ASCII_Integer	N/A	The sol number on which the measurement was taken
2	LTST	ASCII_Real	N/A	The local true solar time (hours) at which the measurement was taken.
3	Board Temperature	ASCII_Real	K	The temperature of the TECP board.
4	Frost Point Temperature	ASCII_Real	K	The frost point temperature measured by the TECP RH sensor.
5	Water Vapor Pressure	ASCII_Real	Pa	The water vapor pressure equivalent to the measured frost point temperature.
6	Uncertainty in Water Vapor Pressure	ASCII_Real	Pa	The estimated uncertainty in water vapor pressure based on the error analysis.
7	Volume Mixing Ratio	ASCII_Real	ppm	The water vapor volumetric mixing ratio obtained from the water vapor pressure and total pressure.
8	Relative Humidity at TECP Board	ASCII_Real	percent	The relative humidity with respect to water ice obtained from the frost point and board temperatures.

Data such as what is shown above can then be graphed and analyzed. For example, below is a graph obtained from the relative humidity sensor, which helps the user understand the relationship between one variable (in this case, mean solar time) and another (vapor pressure). From this data, one could conclude that vapor pressure increases during the day due to sunlight.



Source: (Zent et al., 2010)

5. Safety

5.1. Personnel Safety

5.1.1. Safety Officer

The team has appointed Wendy Yang as the safety officer for the mission. The responsibilities of the safety officer include (but are not limited to): checking for potential manufacturing hazards, suggesting and informing the team about healthy work habits to prevent hazards from overwork in both the office and in the manufacturing sector, scheduling drills for natural disasters, and scheduling practice time for use of safety equipment.

Research into team safety will be reviewed and explored occasionally with safety presentations or modules provided by verified sources: OSHA, Department of Labor, Workers Compensation programs, etc (*OSHA Worker Rights and Protections | Occupational Safety and Health Administration*, 2019, *Workplace Safety and Health | U.S. Department of Labor*, n.d.). The sources will be compiled into a list members can access online for reference, and will be updated periodically.

5.1.2. List of Personnel Hazards

Personnel hazards that have the potential to harm the safety of team members include exterior factors such as pandemics (COVID-19), or problems on the manufacturing floor.

Hazards that may threaten the safety of team members in manufacturing may include:

- Blunt force trauma to the head
- Damage to the eyes from debris
- Damage to muscles and tendons in the lower back, arms, or knees from lifting heavy materials
- Long-term damage to the lungs from inhalation of chemicals or dust
- Long-term damage to hearing
- Bodily harm or loss of life due to a natural disaster

Hazards that may threaten the safety of team members in the office environment may include:

- Severe eye strain
- Repetitive stress injuries from non-ergonomic working conditions
- Mental strain due to stress
- Bodily harm or loss of life due to a natural disaster

Particular hazards that may threaten the safety of team members working at home due to the 2020 COVID-19 pandemic may include:

- Unforseen stress due to home life factors
- Stress due to being confined by the “shelter in place order”
- Bodily harm or loss of life due to contracting COVID-19

5.1.3. Hazard Mitigation

As a response to the current pandemic, the team has decided to complete all nonessential work online, both currently and in the foreseeable future. For those who do have to come in for manufacturing reasons or essential work onsite later in August, hand sanitizers are located in every section of the building. It is mandatory for workers to sanitize hands before/ after any physical task. N95 masks, PPE, and sanitizing wipes will be provided for those who come on site. Used rooms will be thoroughly cleaned at the end of every day. For anything that requires a line, markers are placed at 2 meters apart for proper social distancing.

The team’s safety officer Wendy Yang is tasked with the following to ensure none of the above hazards befall any team member:

- Making sure everyone is well-schooled in using equipment and that no one without a license is allowed to operate heavy equipment such as a forklift or any other large machinery requiring a license

- Enforcing that all team members wear hard hats, properly fitted safety goggles, and earplugs and other such PPE (Personal Protective Equipment) on the manufacturing floor and wherever appropriate. This responsibility includes purchasing appropriate signage as well as verbal reminders and memos.
- Scheduling and running safety seminars with all team members regarding best practice and avoidance of repetitive stress injuries to the lower back, arms, shoulders, and knees.
- Enforcing that all workers wear respirators when there is dust or airborne particles that may be harmful to the lungs.
- Scheduling regular and appropriate drills for the manufacturing team based on the area's tendency towards natural disasters (i.e. tornado, earthquake, fire, etc.)

Aside from potential hazards on the manufacturing floor, other ways the team's safety officer Wendy Yang will mitigate health hazards will be:

- Organizing a safety meeting for office and at-home workers that briefs workers on the latest suggestions for avoiding eye strain and repetitive stress injuries in an office environment
- Scheduling regular and appropriate drills for the office team based on the area's tendency towards natural disasters (i.e. tornado, earthquake, fire, etc.)

For hazards involving mental health and morale, the team project manager Madeleine Graham and deputy project manager Kim Huynh will check in regularly with team members. There will be casual check-ins at the beginnings of team meetings but also follow-ups in case team members are continuously under-performing, late, or have shared that they are having personal issues. Since Madeleine and Kim directly control team member's work loads, if one member is feeling stressed or sick, they can immediately report to the project managers to have their workload lessened. Madeleine and Kim also schedule the project with enough margin/slack so that team members can have enough time to complete their tasks.

5.2. Lander/Payload Safety

5.2.1. Environmental Hazards

General Moon Hazards

The moon varies a lot in temperature, from -173C to 127C, and it is extremely cold inside craters — for example, the inside of Shackleton Crater is estimated to be about 80 to 110 kelvin(Sharp, 2017; *Thermal Extremes in Permanently Shadowed Regions at the Lunar South Pole*, n.d.). The moon has a weak magnetic field, meaning it is strongly affected by the solar wind, which may damage the lander's instruments. The moon does not have a homogeneous gravitational pull — in particular, gravity increases over the marias — which can cause spacecraft to go faster than expected and deviate from the expected flight path(Urrutia, 2019).

Crater Hazards (Explore Space Science Activities, n.d.)
There are several hazards that the inside of a crater may hold, including: central peaks inside; bowl-shaped bottom, which could cause the lander to topple over; brittle surface structure which could unexpectedly collapse under the lander, which could cause the lander to jolt, fall through ice or ground, or topple over(*AIAA Aerospace Research Central*, n.d.). Although regolith is usually a potential hazard for any spacecraft landing on the moon, there should not be excessive amounts of regolith on the crater floor since regolith is usually created by the impacts of micrometeorites, which are more likely to hit the above surface(*Regolith all the way down? | Lunar Reconnaissance Orbiter Camera*, n.d.).

5.2.2. Hazard Mitigation

Cold temperature
Solution: The PIE-L is armed with insulating and heating methods which will work together to make sure that all components on-board will be operational amidst a harsh environment of 90K. The walls of the interior of the lander will have a layer of aerogel and kapton which will serve as an insulator for the heat generated by a cartridge heater/loop pipe system (LHP) system which will produce and transport heated propylene gas throughout the interior as well as the scientific instruments which sit outside of the lander or on the robotic arm.

Overheating from Descent
Solution: The lander may be allowed to rotate during its descent so as to even out the heat from the sun and the cold from space. This may or may not be necessary depending on how long the descent takes.

Solar Wind
Solution: The instruments and equipment the team decided on is space-proven, and solar wind is always an issue

Lumpy Lunar Gravity
Solution: Lander has a semi-automated landing system based on altimeters so it knows how far it is from the ground and will adjust speed accordingly.

Central Peaks in Crater
Solution: If the lander falls or topples over from landing on an uneven surface, it may be able to use its robotic arm to right itself.

Bowl-shaped bottom:
Solution: The chosen crater has a wide, flat area that is several kilometers long for the lander to land safely.

6. Activity Plan

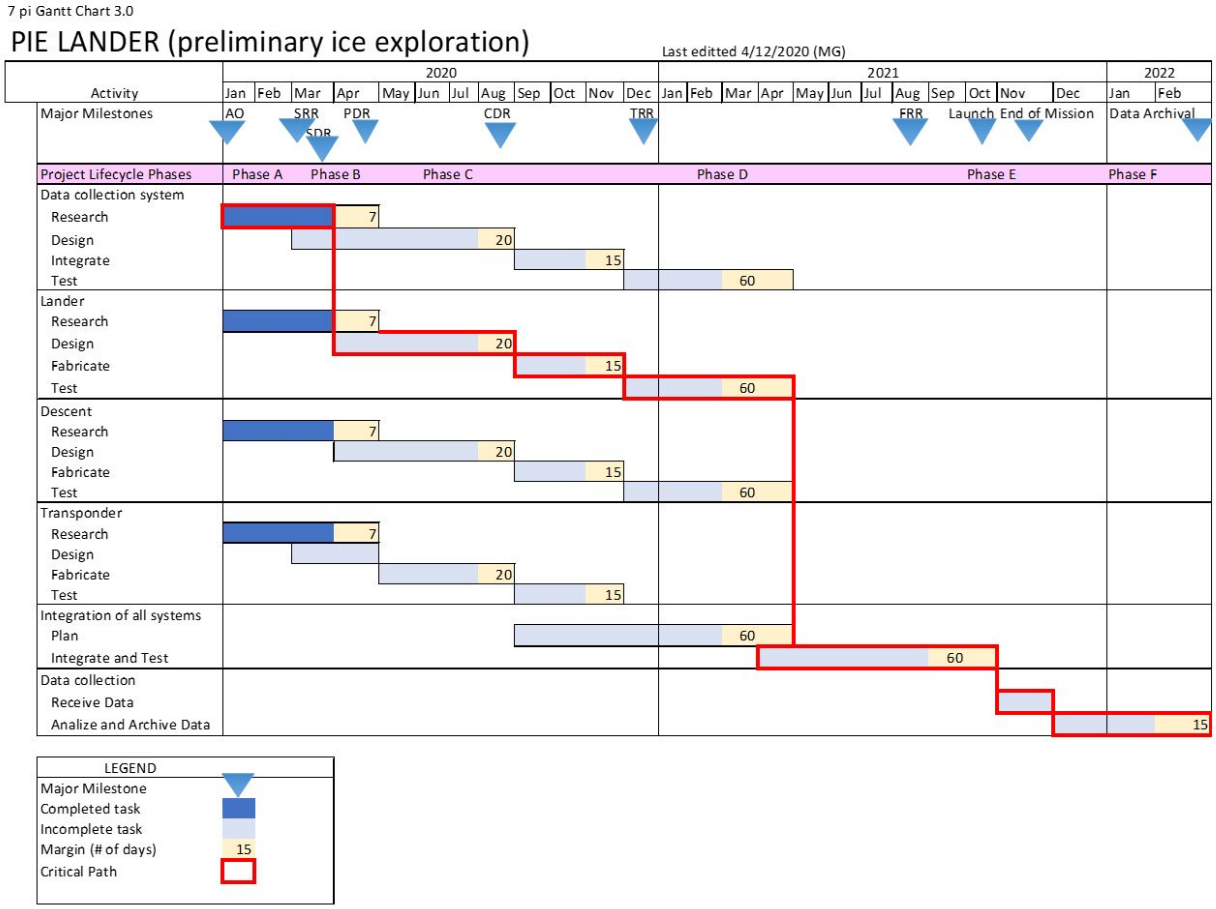
6.1. Budget
The budget will be split into two main categories: paying for the personnel and associated travel costs at the end of the launch year, and paying for the lander.
For administrative costs, the participating team members (7 total) will receive a stipend of $80K a year. The mission itself will only last until February 2022, and by that time the team is only organizing data from the lander experiment. Therefore, the team members will be paid a stipend of $1,213,333.33 to cover 2 years and 2 months. With ERE being implemented in any year but the first, it will only be paid in the two years after year 2020. Any costs for travel will come into play in the second/ launching year. With the ERE percentage of 28% of paycheck, an additional $182,933.33 will be added onto the second and last year.
For travel, the team will allocate 5 days for it with launch day, arriving Oct. 13th, 2021, and staying through Oct. 17th, 2021. Stipends are estimated to be around $3,360 for hotel, $2800 for airfare ($400 per person, American Airlines), $800 for rental cars, and a food stipend of $497 will be given to split among the personnel. This will take place in the second year of launch. The team doesn't plan on pursuing any subcontracts or additional publications, so there will be no money spent for that,

For lander materials, it is recommended that for every 1kg, it will be around $1 million in cost. The payload will be around 10kg after research, so the total will be $10 million estimated for the payload total. The team couldn't get the exact (or any contactor discounted) pricing on equipment, so this is the lander estimate the team will go with for now until the CFD. Research into modifying some of the current instruments for the mission is estimated to be $20,000 per year for the first two years of active research. The total cost per year (without manufacturing, F&A) is respectively, from 2020 to 2022: $10,580,000.00, $743,457.00, $119,466.66. The first year incorporates the whole $10 million material cost, hence the large cost. Manufacturing is 50% of the total cost of materials and supplies, while F&A is 10% of the total cost without extra margins. The total cost for all three years (no margins) is $11,442,923.66. Based on the previous statements, manufacturing is $5 million, while F&A is $1,144,292.37 for all three years. With those two factored in, the total project cost with no 30% margin is $17,587,216.03. With a 30% margin, the project will be $22,863,380.84 total.

The chart below sums up the costs.

Year	Yr 1 Total-2020	Yr 2 Total-2021	Yr 3 Total-2022	Cumulative Total	
PERSONNEL	7	7	7		
Total Salaries	$ 560,000.00	$ 560,000.00	$ 93,333.33	**$ 1,213,333.33**	
Total ERE	$ -	$ 156,800.00	$ 26,133.33	**$ 182,933.33**	
TOTAL PERSONNEL	$ 560,000.00	$ 716,800.00	$ 119,466.66	**$ 1,396,266.66**	
OTHER DIRECT COSTS					
Total Materials and Supplies	$ 10,000,000.00	$ -	$ -	**$ 10,000,000.00**	
Publications	$ -	$ -	$ -	**$ -**	
Hotel	$ -	$ 3,360.00	$ -	**$ 3,360.00**	
Airfare	$ -	$ 2,800.00	$ -	**$ 2,800.00**	
Rent cars	$ -	$ 800.00	$ -	**$ 800.00**	
Food	$ -	$ 497.00	$ -	**$ 497.00**	
Total Manufacturing	$ 5,000,000.00		$ -	**$ 5,000,000.00**	
Total Subcontracts	$ -	$ -	$ -	**$ -**	
Total Participant Support	$ -	$ -	$ -	**$ -**	
Research	$ 20,000.00	$ 20,000.00	$ -	**$ 40,000.00**	
Total Direct Costs	$ 15,580,000.00	$ 743,457.00	$ 119,466.66	**$ 16,442,923.66**	
Total MTDC	$ 10,580,000.00	$ 743,457.00	$ 119,466.66	**$ 11,442,923.66**	
Total Subcontract F&A	$ -	$ -	$ -	**$ -**	
College or University F&A	$ 1,058,000.00	$ 74,345.70	$ 11,946.67	**$ 1,144,292.37**	
Total F&A	$ 1,058,000.00	$ 74,345.70	$ 11,946.67	**$ 1,144,292.37**	
Total Project Cost	$ 16,638,000.00	$ 817,802.70	$ 131,413.33	**$ 17,587,216.03**	
FED FLOW THROUGH (JPL, ARC, etc.)	$ -	$ -	$ -	**$ -**	
					With 30% margin :
Total Project Cost	$ 16,638,000.00	$ 817,802.70	$ 131,413.33	**$ 17,587,216.03**	**$ 22,863,380.84**

6.2. Schedule



The above table describes in more detail the schedule of Team 7pi's PIE-L lander project in more detail from the preliminary analysis, Phase A, to the closeout in Phase F. The data collection, Lander, Descent, and Transponder design personnel all have separate tasks to research and design their own system at the beginning phases, A and B. The critical path shows that the dependency of design and integration for all systems depends first on the scientific research, and then on the lander design, manufacturing, and test results. During phases D and E, the testing of the integration of all equipment is essential to preparation for launch in October of 2021.

The yellow sections of the table show the anticipated margin for tasks. Testing each system has the most amount of slack because tests may reveal design flaws, in which case teams will need the margin time in order to redesign or possibly scrap whole design ideas.

Project Start: Mon, 20-Jan-2020

PIE LANDER (preliminary ice exploration)

Last Edited 4/19 (MG)

TASK	ASSIGNED TO	PROGRESS	START	END	MARGIN	WORK	TOTAL
Getting the Team Together - Leadership Team		73%	1/20/20	4/17/20		65	65
Have our First Meeting	N/A	100%	1/20/20	2/3/20	5	11	16
Create Org Chart	N/A	100%	1/20/20	1/27/20	1	6	7
Team leaders Note who is a member of your "tiger team" and their general availability	Madeleine, Paulina, Wendy	100%	1/20/20	1/27/20	5	6	11
Fascilitate tiger team meetings if necessary	Madeleine, Paulina, Wendy	100%	2/10/20	2/17/20	5	6	11
Reorient goals and update schedule after checking in	Madeleine, Paulina, Wendy	100%	2/17/20	3/2/20	-	11	11
Come up with strategies if behind schedule - if ahead of schedule, come up with stretch goals wi	Madeleine, Paulina, Wendy	100%	3/9/20	3/16/20	-	6	6
Check in with each team member to make sure all are using time efficiently and getting needs m	Madeleine, Paulina, Wendy	100%	3/16/20	3/30/20	-	11	11
Final check ins with each team member about duedates	Madeleine, Paulina, Wendy	100%	4/10/20	4/23/20	-	10	10
Reassign roles going into CDR	(all)	0%	4/26/20	5/4/20	2	7	10
Check in with mission goals and personnel	(new leadership)	0%	(ongoing)	(ongoing)	-	-	-
Reflection on leadership - ask team members for feedback on project and teamwork	(new leadership)	0%	2/1/22	2/8/22	2	6	8
Science Drives the Mission - Science Team		44%	2/3/20	3/23/20	139	36	175
Science: Choose areas to look into from the bullet points on page one, come up with 2 questions	Paulina	100%	2/3/20	2/10/20	2	6	8
Research a selection of landing sites	Mohammed, Jacob, Paulina	70%	2/3/20	3/16/20	2	6	8
Write 1.2 draft (PDR)	Paulina	100%	2/23/20	2/28/20	3	6	9
Write 1.2.1 draft (PDR)	Madeleine	100%	2/23/20	2/28/20	2	6	8
Write 1.2.2 draft (PDR)	Jacob	100%	2/23/20	2/28/20	2	6	8
Write 1.2.3 draft (PDR)	Marcos	100%	2/23/20	2/28/20	2	6	8
Revise 1.2.1 Mission Statement	Paulina	100%	3/22/20	3/31/20	3	8	11
Revise 1.2.2 Mission Requirements	Jacob	100%	3/22/20	3/31/20	3	8	11
Revise 1.2.3 Mission Success Criteria	Marcos	100%	3/22/20	3/31/20	3	8	11
Work with Engr and Budgeting about incorporating science into design	Marcos, Jacob, Paulina	10%	2/24/20	3/16/20	5	16	21
Finalize concept/designs with Engr team - help assess risks	Mohammed, Jacob, Paulina	10%	3/16/20	3/23/20	2	6	8
Finish Science aspect of PDR	Jacob, Paulina, Marcos	75%	4/1/20	4/28/20	5	20	25
Draft Science portion of CDR	Paulina, Marcos, Jacob	0%	5/1/20	6/25/20	15	40	55
Finalize Science portion of CDR	Paulina, Marcos, Jacob	0%	6/25/20	7/22/20	10	20	30
Draft Science portion of TRR	Paulina, Marcos, Jacob	0%	7/22/20	9/29/20	20	50	70
Finalize TRR	Paulina, Marcos, Jacob	0%	11/1/20	12/10/20	15	30	45
Work with Engr in testing process	Paulina, Marcos, Jacob	0%	1/1/21	5/20/21	20	100	120
Draft FRR	Paulina, Marcos, Jacob	0%	5/20/21	6/16/21	5	20	25
Finalize FRR	Paulina, Marcos, Jacob	0%	7/1/21	7/28/21	5	20	25
Travel to launch site	Paulina, Marcos, Jacob	0%	10/16/20	10/16/20	0	1	1
Monitor PIE-L's systems	Paulina, Marcos, Jacob	0%	10/16/20	11/12/20	5	20	25
Analyse PIE-L's data	Paulina, Marcos, Jacob	0%	11/12/21	12/23/21	10	30	40
Take us There! - Engineering Team		31%	2/3/20	3/23/20	160	36	196
Research history of ballistic landings and controlled descents on the Moon/Mars	Max, Paulina	30%	2/3/20	2/10/20	2	6	8
Background research into what is required for transponder	Kim	60%	2/3/20	2/10/20	2	6	8
Work with Science team to decide whether to land ballistically or controlled	Max, Jacob, Marcos	100%	2/17/20	2/24/20	2	6	8
Write 1.2.4 draft (PDR)	Wendy	100%	2/23/20	2/28/20	2	6	8
Write 1.3 draft (PDR)	Max	100%	2/23/20	2/28/20	2	6	8
Write 1.4 draft (PDR)	Paulina	40%	2/23/20	2/28/20	2	6	8
Revise 1.2.4 Concept of operations (graphic)	Wendy	10%	3/22/20	3/31/20	3	8	11
Revise 1.3 Descent and Lander Summary	Max	50%	3/22/20	3/31/20	3	8	11
Revise 1.4 Payload and Science Summary	Paulina	90%	3/22/20	3/31/20	3	8	11
Design sketch of landing craft	Max	80%	2/24/20	3/16/20	5	16	21
Design/programming sketch of transponder	Kim	50%	2/24/20	3/16/20	5	16	21
Finalize designs of transponder	Kim	0%	3/16/20	3/23/20	2	6	8
Finalize designs of lander	Max	85%	3/16/20	3/23/20	2	6	8
Write the remaining Engineering portion of the PDR	Max, Wendy, Kim	40%	3/16/20	4/19/20	10	20	30
Draft CDR	Max, Wendy, Kim	0%	5/1/20	6/25/20	15	40	55
Finalize CDR	Max, Wendy, Kim	0%	6/25/20	7/22/20	10	20	30
Manufacture lander	Max, Wendy, Kim	0%	9/1/20	9/28/20	7	20	27
Manufacture transponder	Max, Wendy, Kim	0%	10/1/20	10/14/20	3	10	13
Assemble science and lander components	Max, Wendy, Kim	0%	10/30/20	11/19/20	10	15	25
Draft TRR	Max, Wendy, Kim	0%	9/1/20	10/12/20	10	30	40
Finalize TRR	Max, Wendy, Kim	0%	11/1/20	12/10/20	15	30	45
Test lander with science feedback	Max, Wendy, Kim	0%	1/1/21	5/20/21	20	100	120
Draft FRR	Max, Wendy, Kim	0%	5/20/21	6/16/21	5	20	25
Deliver lander and all components to launch site	Max, Wendy, Kim	0%	9/1/21	9/21/21	10	15	25
Finalize FRR	Max, Wendy, Kim	0%	7/1/21	7/28/21	5	20	25
Travel to launch site	Max, Wendy, Kim	0%	10/16/21	10/16/21	0	1	1
Monitor PIE-L's systems	Max, Wendy, Kim	0%	10/16/21	11/11/21	5	20	25
Ship's Log - Logistcs, Budgeting, and Administration		41%	2/17/20	4/13/20	117	41	158
Utilize team input to create team schedule/ assign tasks	Kim, Madeleine	80%	2/17/20	2/24/20	2	6	8
Start calculating knowns in budget document - salary, mission expenses	Kim	10%	2/17/20	3/20/20	2	6	8
Schedule 5 days of launch week	Kim, Madeleine	80%	2/17/20	2/24/20	2	6	8
Write 1.1 draft (PDR)	Kim	100%	2/23/20	2/28/20	2	6	8
Write 1.2.5 draft (PDR)	Mohammed	100%	2/23/20	2/28/20	2	6	8
Revise 1.1 Introduction and Summary	Kim/Mohammed	100%	3/22/20	3/31/20	3	8	11
Revise 1.2.5 Major Milestones Schedule	Mohammed/Madeleine	100%	3/22/20	3/31/20	3	8	11
Look at PDR section 1 and assign writing of all section and write duedates	Kim, Madeleine	100%	3/2/20	3/16/20	4	11	15
Look at entire PDR and assign writing of all sections	Madeleine	100%	3/17/20	3/24/20	2	6	8
Work with Science team about desired science equipment and cost	Kim	30%	3/16/20	3/24/20	3	7	10
Work with Engeering team about manufacturing schedule	Kim	30%	2/24/20	3/23/20	6	21	27
Work with Engeering team about cost of craft	Kim	0%	2/24/20	3/23/20	6	21	27
Finalize budget	Kim	5%	3/23/20	4/13/20	5	16	21
Write administative portion of PDR	Kim, Madeleine	70%	3/23/20	4/17/20	5	20	25
Draft CDR	Kim, Madeleine	0%	5/1/20	6/25/20	15	40	55
Finalize CDR	Kim, Madeleine	0%	6/25/20	7/22/20	10	20	30
Draft TRR	Kim, Madeleine	0%	9/1/20	10/12/20	10	30	40
Finalize TRR	Kim, Madeleine	0%	11/1/20	12/10/20	15	30	45
Draft FRR	Kim, Madeleine	0%	5/20/21	6/16/21	5	20	25
Finalize FRR	Kim, Madeleine	0%	7/1/21	7/28/21	5	20	25
Travel to launch site	Kim, Madeleine	0%	10/16/21	10/16/21	0	1	1
Archive and publish data from PIE-L	Kim, Madeleine	0%	1/1/22	2/10/22	10	30	40

The above table shows the specific breakdown of tasks for the group with anticipated group members, margin, and preliminary start dates and due dates for each task. The chart is color-coded to indicate the four general categories of team members and project-related tasks: grey for leadership, blue for science, orange for engineering, and red for administrative and logistics.
The team will continue to update to reflect more appropriate timing when more analysis is performed about how long the individual portions of the next milestones will take. However, prior to that analysis it is vital to reorganize the team into more effective roles based on members' availability and skill set for the next milestone (the CDR). For more information on plans heading into the CDR, please see the conclusion section (Section 7).

6.3. Outreach Summary

The team appointed Marcos Figueroa as the public outreach and social media officer. This officer will be tasked with the responsibility of implementing a three-pronged outreach plan, aimed at students, teachers, and the general public.

Firstly, the plan for our exciting science to reach the general public will be to create a social media presence for Team 7pi. Wendy Yang has graphically designed a team badge for us, which will double as the team's logo on the different social media platforms, such as Twitter, Facebook, Instagram, etc. Our hashtag will be #launchPIE2021 and #wateronthemoon.

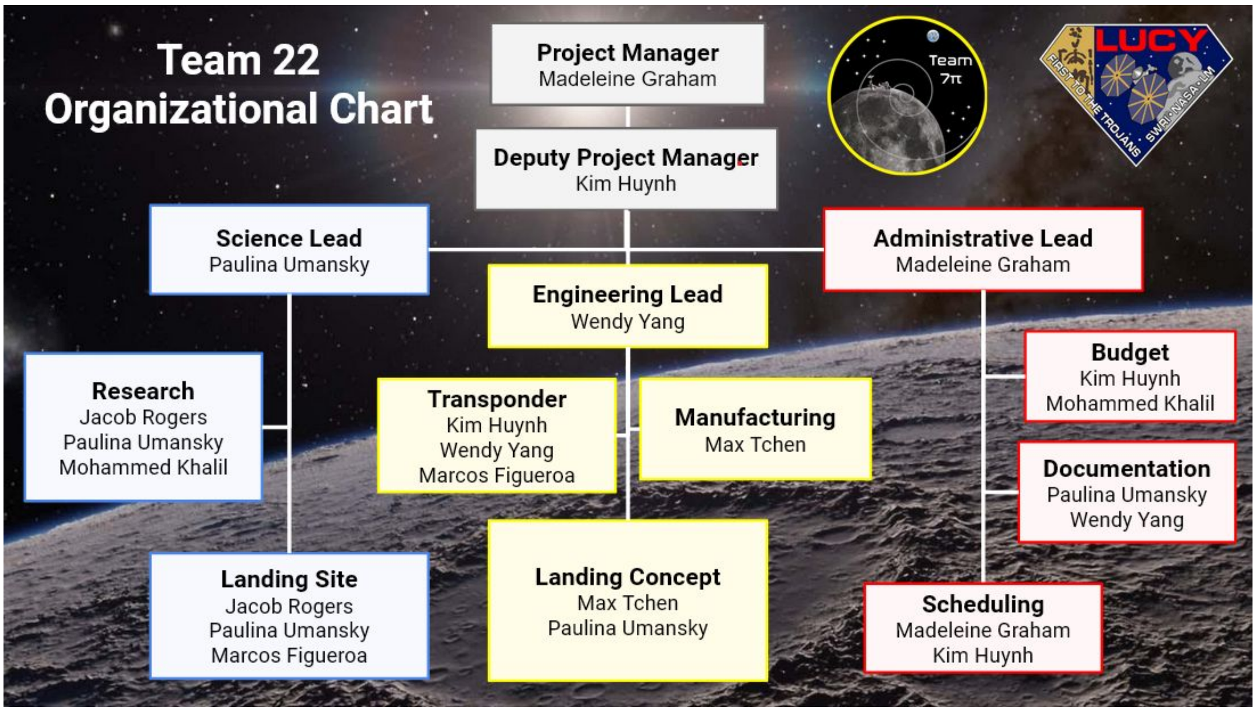
Also, since the team has many key female members, team members will be encouraged to represent 7pi and the mission at Women in STEM events until the launch date.

The second method of outreach is for science educators, and public K-12 school teachers in particular. The outreach officer and other team members will make time to appear in science classrooms and assemblies in their alma maters and local schools. Since the team is fairly spread out along the western states of the US, there is a decent distribution of this effort to inspire children from many different places in the US.

Lastly, the team will turn its eye towards outreach to community college students in the form of offering virtual internship experience. This will benefit the community because more community college students will have work experience in a science field, and more community members will know about the mission.

6.4. Program Management Approach

At the beginning of this project, the team was brought together by the leaders of ASU's L'Space program. During the initial four weeks, certain assignments were given out to help the teams to get going: i.e., creating an organization chart, and holding separate team meetings. As a result of this, the teams self-organized early but in a non-organic way. Here is the initial organization chart turned in by the team as assigned:



The above chart shows that the team separated itself into smaller teams based on expertise and the needs of the project. The small teams were generalized into three different umbrellas: Science, Engineering, and Logistics/Administrative. The Science team was divided into a Research Team and a Landing Site Team. The Research Team members refined the goals of the mission and chose instrumentation they wished to use. The Landing Site Team used the product JMARS Beta and interpreted the data using that tool to come up with options for a landing site from which the whole science team could choose. The Engineering Team was also split into smaller teams consisting of the Transponder Team, Manufacturing Team, Landing Concept Team. The Transponder Team figured out how to program a transponder for communication. The Manufacturing Team designed the lander and figured out materials, budget, and manpower for manufacturing the lander. The Landing Concept Team designed the method of landing for the lander. The Logistics Team consists of the Budget Team, Scheduling Team, and Documentation Team. The Budget Team helps manage and allocate the budget. The Scheduling Team decides the timeline of when the scientists arrive at the launch site. The Documentation Team helps document major decisions and objectives of the teams.

At the beginning, it was up to leadership to come up with discrete goals for each team (i.e., contact all team members and get acquainted). Every week has a 40 minute check-in meeting with the Project Manager. The Science, Engineering, and Logistics teams all moved mostly independently from one another, but team members worked together in order to make decisions. The project manager organized the group into smaller teams each with a separate team leader so as to have another method of communication and sharing responsibility. This proved both effective and not effective. Some individuals are able to take on a leadership role while others only will hold the title in name and cannot be counted on to take initiative. After time, the team members started to get to know each other's strengths, habits, and abilities better, and after that point, those who took initiative could be called "leaders" more than others, but not necessarily in name. In short, the team could not be said to be a group of smaller teams, but rather a few individuals with greater initiative than others occasionally being able to count on the help of other team members with busier schedules and/or less experience or initiative.

Some issues that came up were four team members dropping out due to unforeseen circumstances. Although this may have made communication easier, since the team being smaller meant that there were fewer people who needed to be able to communicate, this also meant that fewer people were available to do the work. Two of the four team members who ended up dropping out of the project were also not open about their inability to keep up with the work, and so the team ended up waiting on people who were unresponsive, not wanting to leave anyone out. This led to some time being wasted worrying about why some members were not showing up to meetings. This issue was overcome by sending various emails and messages to those members at first making sure they were in the loop, and then asking bluntly whether they were going to be available.

Another issue that came up was that since all work was done virtually, sometimes it was difficult to get in contact with some team members. Though team members seemed to be available to work, they were not clearly communicating their work schedules so that it was obvious when was a good time to anticipate questions being answered or decisions being made. This affected some decision-making, as, for example, it is difficult to design a landing mechanism when one is not certain where the landing site is located. The project manager created a spreadsheet where team members were encouraged to fill in times where they were going to specifically set aside time to work on this project. This worked to moderate effect. The project manager also reached out to absentee members to offer ways to help facilitate meetings. This was successful in fostering a more consistent work ethic. In the end, the most effective way to facilitate more productive communication among team members was to assign tasks to others by name and to hold them accountable.

Finally, the coronavirus pandemic took its toll on the members of Team 7pi. One team member had to drop from the project because they had to move out of the country. At least three others were forced to pick up their lives and move because they were living in University dorms where the virus could too easily spread amongst students. At least one member was assigned a large school project because classes were cancelled. Team 7pi weathered the situation well, all things considered. The scheduling team had built in a significant amount of margin for writing this document, so that disasters such as the COVID-19 pandemic and other life events that came up (death in the family, sickness, etc.) could be dealt with leniently and with compassion.

All-in-all, even though the team members suffered through personal inconveniences and losses, it was a great morale booster to hold our virtual meetings and know that members would be welcoming and non-stressed about the project.

7. Conclusion

PIE-L is a lunar lander that will use its instruments to assess the existence, amount, and distribution of water, and the elements that typically surround water reservoirs in the craters on the moon’s south pole. The mission is crucial for humanity’s journey from the Moon to Mars because the knowledge of the state of water on parts of the moon (in regards to it’s locations, concentration, and potential contaminants) will help inform decisions for human lunar settlement. PIE-L can be a stepping stone towards making permanent lunar settlement a possibility.

The lander will make a powered descent into Shackleton Crater located at the moon’s south pole. The payload of scientific instruments includes the following: the Thermal and Electrical Conductivity Probe (TECP), the Dynamic Albedo of Neutrons (DAN), and the Alpha particle X-Ray Spectrometer (APXS). These instruments will be used to achieve the mission’s scientific goals, which are: 1) verifying the existence of lunar water ice 2) collecting data on the depth and distribution of water on the moon and 3) gathering data on elemental distribution on the crater floor. The payload will also include a transmitter for communication back to the transponder, which earth, a thruster system for the powered descent and reorientation, an onboard computer for data storage, processing, and controlling instruments, a star tracker and altimeter for descent, a battery for power, and a heating system for operating in the extreme cold.

Pending approval of this PDR, the team will start to work on the CDR (Critical Design Review) for PIE-L. The CDR will elaborate on the following areas that this document does not address:

- Detailed schema for cost in manufacturing
- Detailed requirements for material performance and justification of materials and design.
- Stricter definition of roles and personnel, location of manufacturing, and equipment to be used in manufacturing.
- More detailed risk analysis including the items above.
- Operational requirements for technical instruments.
- Defining what testing is to be done to defray identified risks.
- Research plans for the Short Range Emitting and Receiving Instrument (SHERI), a modernized and lightweight version of the DAN which the team hopes to create in order to fit the mass constraints of the mission

Team 7pi is excited to be the stepping stone from which the next “giant leap for mankind” can occur.

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