VELOS

Variable Exploratory Lunar Observation System

Arizona State University	**Final Technical Paper and Proof of Concept Demonstration**
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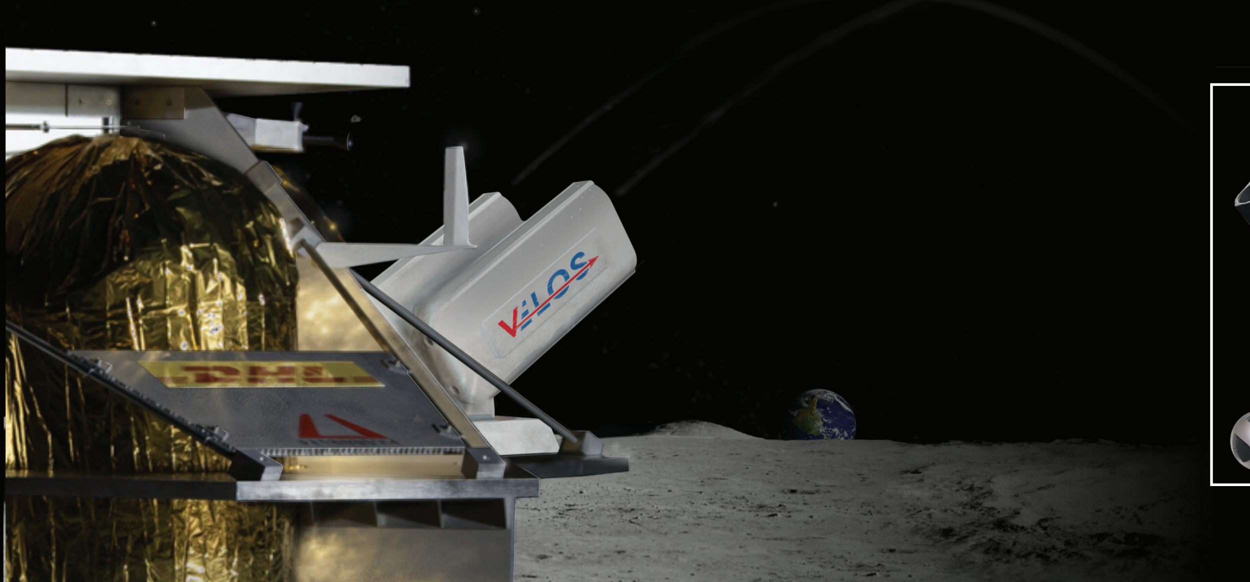

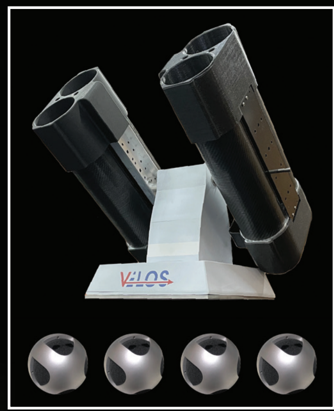

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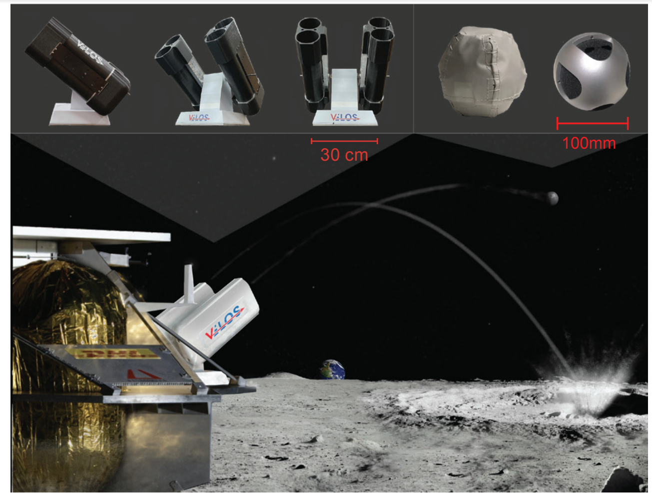
Concept Synopsis

The Variable Exploratory Lunar Observation System (VELOS) is a spring launched multi-probe sensor system that is designed to be launched from the lander over 100m into and around the PSR for data collection.

The system consists of a launcher and four probes that are equipped with:

- Temperature sensors: internal and external
- Inertial measurement units (including accelerometer and magnetometer): internal and external
- Designed to accommodate additional sensors such a neutron spectrometers.

Each probe can collect data for up to 5 hours and relay information wirelessly back to the lander via a mesh network.



Innovations

VELOS is an innovative approach for exploration in an unknown environment by providing a solution that is reliable, versatile, and scalable. It's novel launcher mechanism allows for the design of probes with different sensor payloads and allows the science mission to choose where those sensors should be deployed. Because each launch tube is identical, it allows for the number of probes to be scaled uniquely for the mission profile. The launchers spring-based mechanism reduces mechanical components while providing a solution that is reliable in a critical mission. The VELOS system will enable future science missions to the Moon and Mars by providing a low cost exploration system that can reliably launch multiple types of sensors for valuable data collection that can be designed by scientists or students for exploring and enabling the next crewed mission to the moon.

Proof-of-Concept Testing Results & Conclusions

Launcher Testing:

- Maximum launch distance achieved: 16.5m(equates to 100m on the moon). Over 20 tests performed at various distances.
- Vacuum Testing: tested in vacuum below 2e-2 Torr for over 2hr
- Communications Systems: Mesh network test, 132kb max data transfer in15.5s window.

Probe Testing:

- Launch Impact Testing: Successful launch test and data collection of 2 probes, drop test simulation performed.
- Thermal Vacuum Chamber Testing: 2 hours total, 40 minutes below 2.2e-2 Torr and -120C
- Thermal Vacuum Simulations: PSR conditions simulated, successful probe operation for 5 hours before critical temperature reached.

Conclusions: Through development and testing, VELOS showed successful proof-of-concept and advancement to TRL 4 with progress toward TRL 5.

EXECUTIVE SUMMARY

The Arizona State University VELOS project supports NASA's extraterrestrial exploration efforts by offering a design for exploring the permanently shadowed regions of the lunar surface that is configurable, reliable, and scalable. This project addresses the Big Idea Challenge of developing "Capabilities to explore and operate in Permanently Shadowed Regions (PSRs)" by developing VELOS: Variable Exploratory Lunar Observation System, a configurable multi-probe exploratory system that will be launched from the lander over 100 meters into a PSR. Each probe is equipped with a configurable suite of sensors designed to optimize data collection potential and survive the harsh lunar environment. The VELOS probes are deployed from a launcher designed to integrate with any CLPS lander. VELOS will allow NASA to gather more data in and around the PSRs by providing a scalable solution to exploring unknown regions of the lunar surface.

The launcher uses preloaded springs designed to distribute probes in and around a PSR to maximize data collection potential. The launcher consists of four tubes, each of which uses a spring and release mechanism to launch a probe on a preset trajectory. The launcher will deploy a total of four probes. One probe will be deployed in the vicinity of the lander to collect data in and around the landing site, one probe will be launched to a medium distance from the lander, and one probe will be launched at the maximum distance to reach within the PSR. The maximum launch distance of each probe is calculated to be ~100 m with the current suggested spring, but could be increased or decreased depending on mission specifications. The probes are designed to house two temperature sensors (one internal and one on the outer shell), two single chip Inertial Measurement Units (IMU), and a miniaturized neutron spectrometer for determining the presence of hydrogen, putatively in water ice. During Phase I, the VELOS team worked with ASU professor, Dr. Craig Hardgrove from the School of Earth and Space Exploration, who has been developing neutron spectroscopy sensors specifically for detecting hydrated materials on the lunar surface (he is the P.I. of the Artemis-1 LunaH-Map CubeSat mission). The team was able to complete a preliminary design of the sensor probe that is capable of supporting Dr. Hardgrove's novel technology to collect definitive data on the presence of water ice within the PSRs. After landing, the probes will begin collecting IMU, spectroscopy, and temperature data and will establish a mesh network to communicate wirelessly with the lander. In the event that communication cannot be established, the probe will store the data it has collected in its 16Mb flash storage. At the end of the mission If the probes in the field are not able to establish a mesh network connection with the launcher, the launcher will deploy a final probe to act as a communication relay for all probes in the field. During this final launch, the relay probe will receive the data from the deployed sensors, then transmit the information back to the lander during its flight. After the relay probe lands it will again attempt to establish a network with the disconnected nodes and the launcher to relay the data back to the lander.

The VELOS team conducted proof-of-concept testing to validate each subsystem and the overall operation of the system. To test each subsystem, the team worked with ASU laboratories to facilitate testing. Thermal-Vacuum chamber tests were conducted on the probe, and vacuum only tests were conducted on both the probe and launcher. The probe was successfully able to collect and transmit data in thermal-vacuum chamber conditions during which the conditions were below -120C and 2.2e-2 Torr for 40 minutes. The launcher and probe were able to successfully sustain operation under vacuum conditions of 2.2e-2 Torr for over 2 hours at ambient temperature.

Launch testing was conducted to validate both the launcher's capability to deploy a probe and the probes ability to undergo stresses during launch and impact. During testing, the launcher was able to successfully actuate and launch the probe over 16.5m in Earth gravity which is equivalent to 100m in lunar gravity. In addition, full proof-of-concept testing of the system was conducted using two probes launched at different distances and headings. These probes were monitored and were able to successfully maintain operation after launch.

EXECUTIVE SUMMARY CONT.

Virtual testing was completed on the launcher and probes for advanced thermal testing, structural load testing, vibrations testing, and drop testing using the ANSYS Simulation Environment. Simulations were used to simulate a drop test impact of 12.72 m/s on sand-based regolith. Thermal simulations were validated with test data and used to simulate the probe under PSR conditions. Random Vibration simulations were conducted per NASA NTSS General Environmental Verification Standard (GEVS) to identify components weakness for future Technology Readiness Level (TRL) advancement.

Through the BIG Idea Challenge, the VELOS team was successfully able to test the proof-of-concept prototype to achieve TRL 4 as well as make significant progress to identify and eliminate barriers to advancement to TRL 5.

PROBLEM STATEMENT AND BACKGROUND

The challenge being addressed is to develop “capabilities to explore and operate in PSRs”. Little information is known about the regions in and around the PSRs. Designing a complex system that can work reliably in the wide range of potential conditions is difficult. As a result, data collection in the PSRs is of the utmost importance to be able to accurately understand the region and potential resources. Therefore a scalable system that can adapt to the changing needs of scientists is important. Devices currently used for maneuvering the Moon landscape have traditional mobility form factors such as four-wheel rovers. The energy, weight, cost, and reliability required for these traditional vehicles to operate in a PSR where solar and nuclear power are not an option pose significant challenges. The unpredictability of the characteristics of the PSRs requires flexible and adaptable design for data acquisition and retrieval. Lightweight distributed sensors provide an opportunity for data acquisition and environment mapping that is unprecedented. This is the basis for the solution proposed. The approach taken to address this challenge is to develop a spring launched multi-probe system that provides a configurable, scalable, and reliable solution for exploring the unknown region in and around the PSRs.

The overall approach is to use small low cost sensor probes that can be easily distributed in an area to collect data at various points near an object of interest in the PSR. This system architecture provides different solution modalities compared to the traditional rover - base station architecture such as collecting data at multiple positions simultaneously, having the ability to put different sensors on each probe, and the capability for the probes to serve as data relays. The spring based launcher is designed to be very reliable by reducing the number of moving components and to accommodate different sensor probes.

Once the probes are launched from the lander, each probe communicates as a node of a mesh network which benefits from having numerous nodes in the field to increase line of sight opportunities. Each probe serves as a node in the mesh network and can act as a relay back to the lander in the network. In addition the mesh network can facilitate other entities joining the network such as small rovers or other vehicles that are within line of sight of a probe. This can be used to extend the effective communications range and position localization for small vehicles in the area.

PROJECT DESCRIPTION

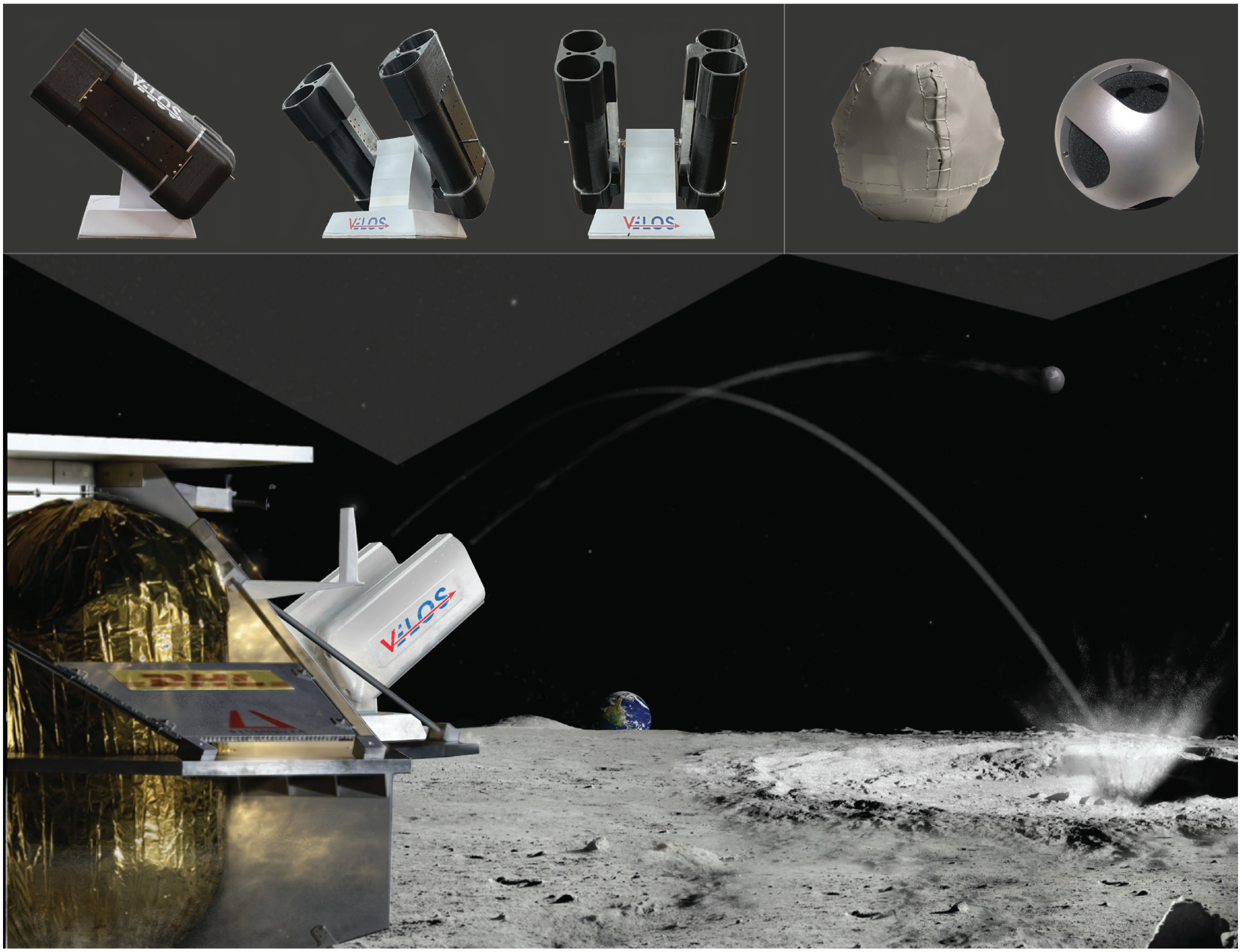


Figure 1: Graphic rendering of VELOS launcher on a CLPS lander

VELOS is designed to explore and collect data in a PSR by deploying four softball-sized spherical probes into and around the PSR from a launcher mounted on the lander. The system is designed to operate with any CLPS lander and fully meets CLPS payload capability requirements. Each probe has a configurable suite of sensors with the base configuration including but not limited to: temperature sensors, Inertial Measure Unit, and options for additional sensors such a neutron spectrometer. The probes include a wifi radio to transmit data over a mesh network and an onboard battery system that will power the sensors and maintain temperature control inside the probe for up to 5 hours of continuous operation from the time it is launched from the lander. The probes will transmit data every second to the launcher over the mesh network, which will transfer the data to the lander. In the event that they cannot establish a communications handshake with the launcher, the probes will store the data and at the end of the probes' operational life, a final probe will be launched which will act as a communications relay while in flight and on the ground to transmit data from the probes to the launcher before line of sight is lost.

PROJECT DESCRIPTION CONT.

To launch the probes, VELOS uses preloaded springs that will be loaded on Earth. The launcher tubes are mounted to a turret with rotational degrees of freedom in the azimuth and altitude axis. Once the lander has landed and the PSR has been identified using the landers on-board cameras, the launcher will rotate using the azimuth axis to point in the direction of the PSR and rotate the altitude axis to set the launch distance to reach the PSR. Each probe will be launched sequentially and the distance launched for each probe can be pre-programmed or chosen based on camera data collected by the lander. This will allow the system to be adapted for a variety of mission profiles to collect data in the near vicinity of the lander, near the PSR, or in the PSR.

VELOS was developed to be reliable, scalable, and configurable. With this in mind, development focused on demonstrating the core capabilities of the system. This includes: launching a projectile 100m on the lunar surface, proving the probes ability to undergo the loads of launch and impact, the probes ability to operate in the PSR, and communication between the probes and the launcher.

PROBE SUBSYSTEM

The VELOS probe was designed to be launched from the lander at a max velocity of 12.72 m/s and safely carry a small payload of sensors that could collect data on the lunar surface and inside the PSR for a duration of 5 hours. In addition, the probe was designed such that the sensors inside could be configurable to fit the needs of the mission. During development, the probe was broken down into electrical and the mechanical subsystems.

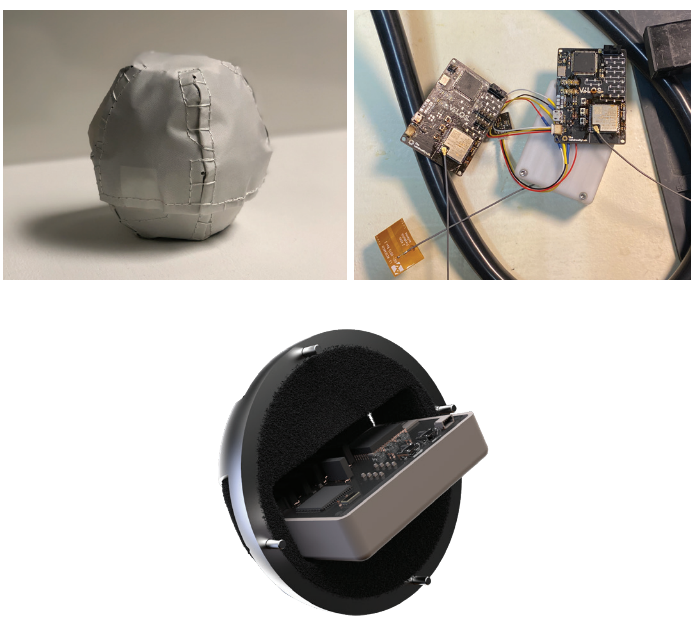


Figure 2: Fully assembled probe with MLI outer blanket (left), probe PCBs (right), probe sensor (lower)

Electrical Subsystems

For the proof-of-concept, the probe was designed to include the following sensors:

- 2 temperature sensors: internal temperature sensor for heating control, external temperature sensor for regolith monitoring.
- 2 Inertial Measurement Units (IMU): 6 degree of freedom accelerometers plus 3 degree of freedom magnetometer. External IMU for measuring impact acceleration for information about the regolith and internal IMU for measuring the acceleration on the electronics.
- Capability to include LunaH-Map Neutron Spectrometer onboard for measuring putative water-ice levels in the PSR.

The sensor data is processed by an ESP32 system-on-chip microprocessor which was chosen for it’s built in wifi functionality. In addition, the probe PCB includes an ATMEGA128P microcontroller unit (MCU) for lower level functionality, robust performance, and flight ready component options.

The power for the electronics is provided by a 4000mAh lithium-polymer battery which was designed to supply enough power for the probe to collect data for 5 hours in the PSR and to maintain a minimum operating temperature for the electronics and battery.

Mechanical Subsystems

The primary functionality of the probe is to collect data and transmit that data back to the launcher. To do that, it needs to survive the impact of being launched as well as the thermal environment of the PSR. The main PCB and battery were designed to be housed in a High Density Polyethylene (HDPE) enclosure. HDPE was chosen for it's non-conductive, low temperature tolerant, and radiation shielding material properties that have been evaluated for space applications [1]. The HDPE electronics enclosure was then wrapped in an MLI blanket that was designed by AeroThreads (Riverdale, MD) and includes 10 layers to directly insulate the electronics. Between the MLI wrapped electronics enclosure and the outer shell, the probe includes a shock absorption layer to protect the electronics from impact using an isotropic energy absorption material. The material chosen for the probe was Duocel™reticulated vitreous carbon (RVC). The RVC foam is enclosed in a protective shell made of 6061 aluminum that includes windows for weight reduction and for optical viewing if the sensor payload requires it. The outer shell of the probe was then wrapped in an MLI blanket designed and manufactured by AeroThreads that includes 10 layers to shield the probe from external solar radiation if the probe is deployed outside of a PSR and further reduce heat loss while in the PSR. The MLI is wrapped in an outer layer of Beta Cloth to protect the MLI during launch and impact.

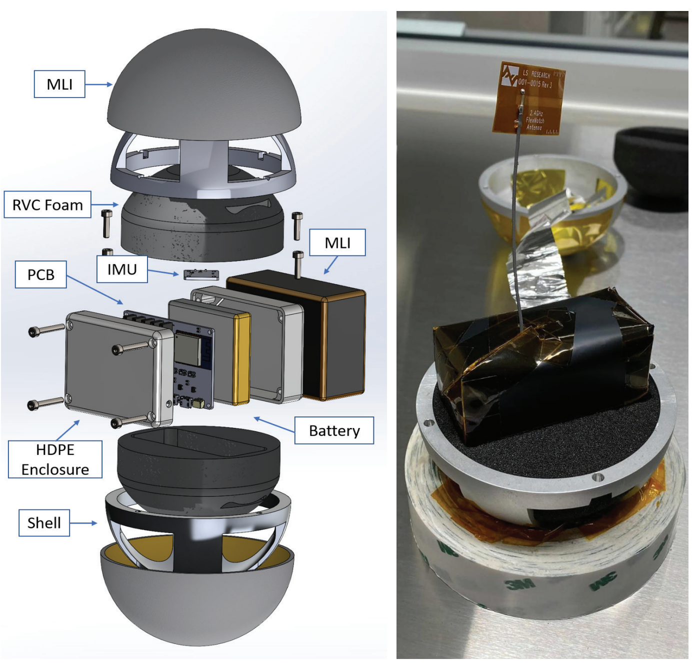


Figure 3: Probe CAD model exploded view (left), partially assembled probe (right)

Probe Sensor Payload Configurations:

LunaH-Map Neutron Spectrometer Integration

VELOS was designed to be able to launch various sensor payloads that could be configured for the specific science mission. To showcase this capability, the team worked with ASU's Dr. Craig Hardgrove to develop a preliminary concept of the probe that could carry a small version of the Neutron Spectrometer developed for the Lunar Polar Hydrogen Mapper (LunaH-Map) mission. To accommodate the sensor, the probe form factor was elongated such that it could still fit within the current launcher system but would allow more room for the sensor payload. This is a key functionality of VELOS that can enable many different form factors to work with the same system.

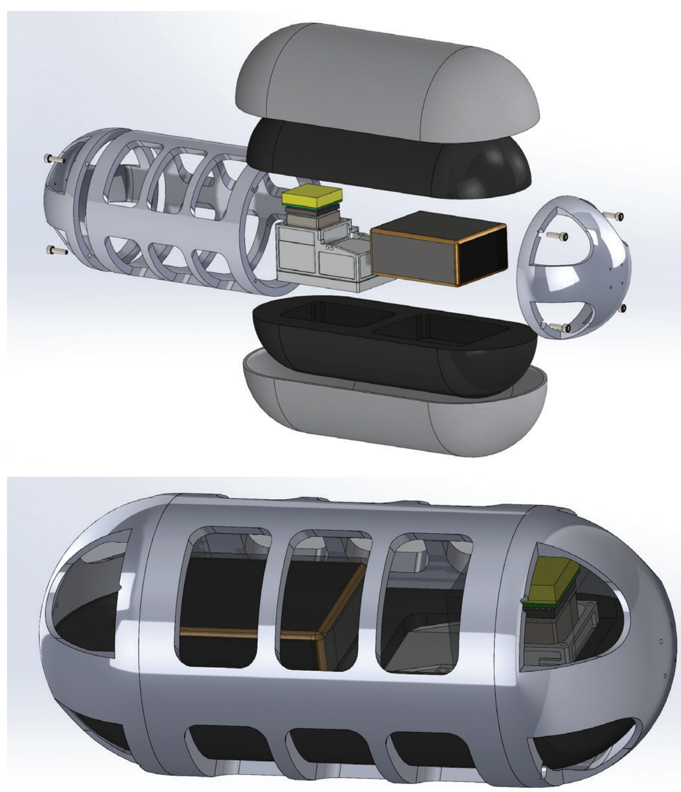


Figure 4. VELOS probe preliminary design to accommodate LunaH-Map Neutron Spectrometer

LAUNCHER SUBSYSTEM

The VELOS launcher was designed to deploy the probes over 100m on the lunar surface to reach the PSR from the CLPS lander. The launcher was designed with the assumption that the lander would land within 100m of the PSR and that the launcher would be mounted on the side of the lander that is oriented towards the PSR. With these assumptions, the launcher was developed to launch four probes in and around the PSR. To best accomplish this task, the launcher has degrees of freedom in the altitude and azimuth axis. Each axis has a maximum of 0-180 degree rotation and would only be limited based on the mounting position limitations of the lander. In addition, the launcher has four spring loaded probe deployment mechanisms that can be individually actuated, allowing for different probe placement options. The launcher's electrical system is designed to control the actuation of the launcher, deployment of the probes, and data communications with the probes in the field.

Figure 5: Fully assembled launcher in testing (above)

Electrical Subsystems

The electrical subsystems of the VELOS launcher include the PCB, the actuator motors, and the spring release mechanism. The launcher PCB is designed using the same architecture as the probe. It includes an ESP32 wifi module for communications and an ATMEGA128P MCU for lower level control of the actuators and release mechanism. The launcher PCB is designed to operate within the power specifications given for the CLPS landers. It can operate anywhere from 12V to 28V. Assuming a 28V input voltage, the launcher consumes a maximum 7.18 watts during standby. The power consumed during actuation is roughly 32.4 watts. Additionally, the power consumed during launching is 38.8 watts for four pulses lasting one second each. For proof-of-concept, the launcher uses low resistance nichrome wire to hot-wire cut and release the spring hold down mechanism. The wifi radio on the launcher is designed to connect to the probes via a mesh network and relay data from the probes to the lander.

The electrical schematic for the launcher PCB is broken up into seven subsections. MOSFET Switches: which isolate the high power MOSFETs from the MCU, and allow for low input control of high load switches. Step-Down Converter: which efficiently steps down 28V to 5V for the MCU and 3.3V for the Wifi module. Stepper Motor Controller: which isolate the high power actuators from the MCU, and include current limiting and microstepping abilities. ATMEGA128 MCU: which is a high performance programmable microprocessor circuit used to control the actuators, release mechanism, and wifi communication (available in space rated package). ESP32 Wifi and Bluetooth Module: which is a Wifi radio used to communicate with the MCU via Wifi and I2C. Voltage-Level Translator: which allows the 3.3V ESP32 to communicate with the 5V MCU via I2C. USB and Serial Converter: which programs and communicates with the ESP32 via UART.

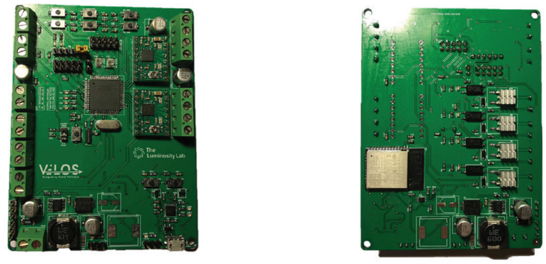


Figure 6. Top and bottom of populated launcher PCB

Mechanical Subsystems

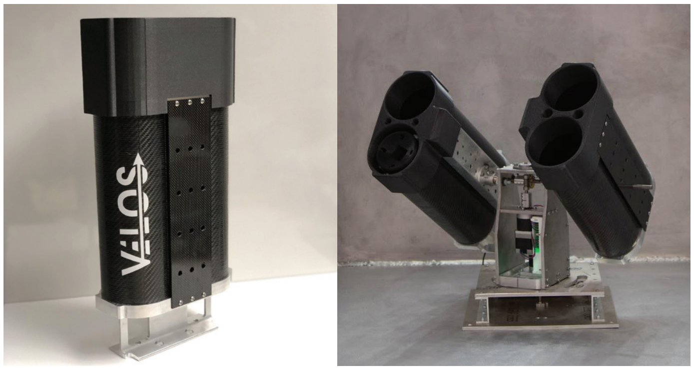


Figure 7. Launcher turret and launch tubes

The launcher mechanical systems were designed and machined in-house by the VELOS team to actuate and launch the probe 100m. Preliminary calculations were performed using principles of conservation of energy and projectile motion to calculate the spring required to launch the probe 100m on the Moon. From a preliminary projectile motion analysis, it was found that the probe would need to leave the launcher at a velocity of 12.72m/s to travel 100m on the lunar surface (see Calculations Section in Appendix). The spring constant was calculated to provide the appropriate amount of energy to accelerate the probe to the required exit velocity. With the desired exit velocity as the goal, the development started with small light springs to test the concept and gradually increased the spring rate until the desired launch distance was reached.

The team designed a turret that used stepper motors and reduction gear boxes to achieve accurate position control with minimal power requirements. In the altitude axis, the turret was designed to use a worm gear to prevent backdriving and eliminate the need for holding torque.

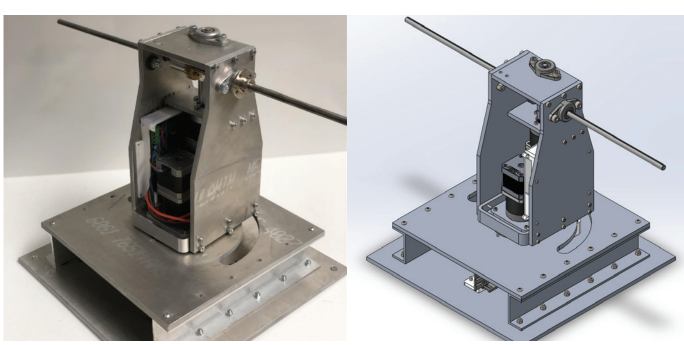


Figure 8. Launcher turret and base

The launch tubes were designed to hold the spring, plunger, and hold-down release mechanism. The plunger and spring mechanism were iteratively developed during testing to enable the use of various springs and to provide a stable and reliable launch mechanism. Through these interactions the team developed a novel plunger design that uses Polytetrafluoroethylene (PTFE) low friction slides that are spring loaded using linear springs to align the plunger in the tube. This was a critical innovation in the design because it does not require a precision machined barrel or plunger surface which greatly reduces the complexity of the system. In addition, the springs which apply a radial force on the PTFE slides allow for thermal expansion and contraction of the plunger and barrel and reduce potential for binding.

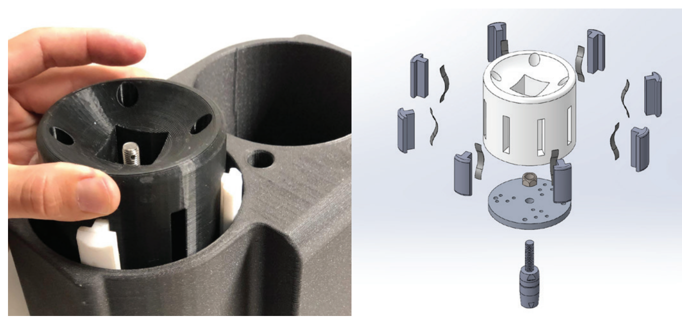


Figure 9. Plunger with PTFE (white) guides for smooth actuation and fit in the barrel

The spring is held in compression using a hold-down release mechanism (HDRM) proposed by Thurn et al. [2]. It uses a high strength dyneema cord that is attached to the ends of the spring using a custom compression plate. The cord extends out of the back of the launch tube where it can be cut using a spring tensioned nichrome hot wire cutter. This provided a low cost and effective solution that could be quickly iterated on while also serving as a functional stand in for the intended flight ready electronic HDRM “Frangibolt” made by Ensign-Bickford’s TiNi Aerospace division.

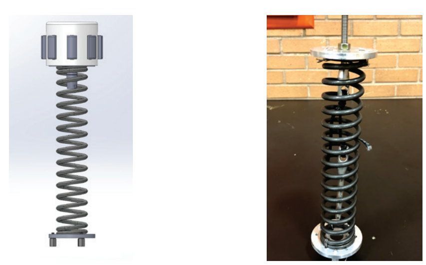
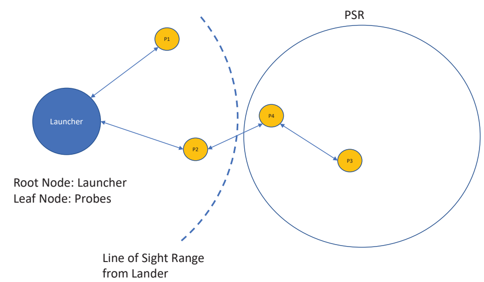


Figure 10. Spring and release mechanism subassembly outside of the barrel

COMMUNICATIONS SYSTEM

The lander and probe utilize a wifi mesh network to transmit data. The mesh network allows the launcher to communicate with each probe and to monitor which probes are not on the network. This allows for the launcher to identify which probes are out of line of sight after the probes have been launched. Once a probe is launched it will start transmitting its sensor data to the launcher every 1 second. If a probe cannot connect to the launcher, it will store its data and attempt to reconnect once every second so that when it can reestablish connection, it can quickly transfer as much of it's stored data as possible. The current concept of operations for the mission is for the launcher to deploy three probes in and around the PSR. One probe would be deployed close to the lander to collect data from nearby regolith, one probe would be deployed an intermediate distance from the PSR and one probe would be deployed into the PSR. In the scenario that one or more probes are not able to establish line of sight communication with the launcher but can establish a connection with another probe which is connected to the launcher, then the network is intact and communication can occur. This is called mesh hopping and is critical to the operation of small electronics in the lunar environment. In addition to the probes serving as a mesh network to relay information back to the launcher, they could also be used by other small vehicles in the area to mesh hop information back to the lander via the probe mesh network. In the event that a probe or group of probes is completely isolated from the network, the launcher can deploy the 4th and final probe to act as a communications relay. Based on projectile motion calculations (see Calculations in Appendix) this probe has a maximum flight time of 15.5s when launched and can transmit a maximum of 132kb of data during this window. Once the probe lands it will attempt to establish connection with the other probes in the field allowing it to serve as the missing link in the network. This concept is shown in Figure 11 below where Probe 4 is strategically launched between Probe 2 and Probe 3 to provide the missing link of communication allowing the probes to node hop data back to the lander.



Figures 11. Mesh network diagram for Lander and Probes

VIRTUAL REALITY ENVIRONMENT FOR EDUCATION, TESTING AND TRAINING

A virtual reality (VR) environment was developed for VELOS for the purpose of educating, testing, and training personnel working with the VELOS system. VELOS was designed such that scientists or student teams could design, build, and deploy a probe for a specific science mission. The VELOS VR environment was designed to communicate the critical functionality of VELOS, it's subsystems, and its operational ability. The VR environment allows the VELOS team to quickly communicate the concept of operations to CLPS providers, teams of students or scientists designing probes for future missions, or to k-12 students to inspire them to pursue STEM fields.

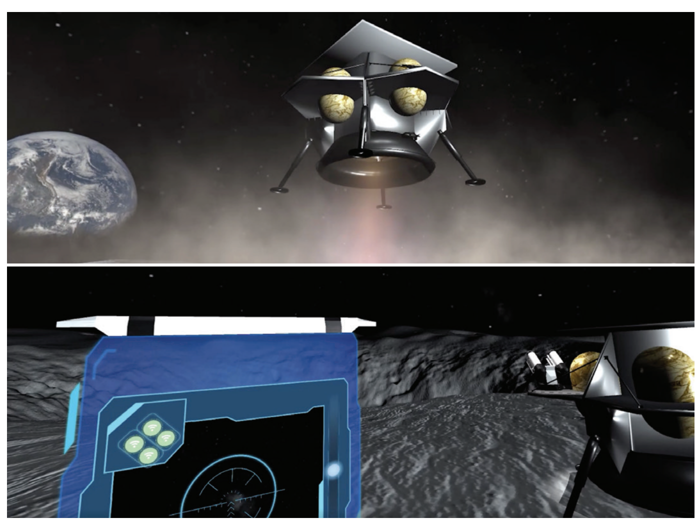


Figure 12. VR Environment showing the CLPS lander and launcher with a manual interface

VIRTUAL REALITY ENVIRONMENT FOR EDUCATION, TESTING AND TRAINING CONT.

The environment consists of a set of virtual display stations that are positioned around a PSR. The user enters the environment as a 1st person viewer of the CLPS mission. Although it is well understood that the CLPS missions will be uncrewed, the 1st person view allows the user to interact and immerse themselves in the process. Once the viewer learns basic information about the PSR and mission goals, they teleport to a station to watch the CLPS lander approach. Once the lander has touched down, the viewer is introduced to the VELOS launcher and probe and how it operates with the lander. They are then prompted to go through a manual launch sequence where they can pick and choose where to launch the probes. Once the probes have been launched they are shown a data dashboard showing the types of data that the probes would relay back to the launcher.

This environment lays the foundations for future development for training and education as well as testing. VR environments are optimal for testing complex mission procedures as it requires advanced details of the system operation. The VELOS VR environment will enable and inspire future development of the VELOS platform. See attached video for VR walk through.

The team used Unity 3D's game engine with the XR Interaction Toolkit. The application is built for an Android device- specifically the Oculus Quest headset. The lunar environment includes a custom skybox and a 3D lunar terrain sculpted using the Unity Terrain Toolkit. All 3D models and 2D interfaces were created by the team as well as interaction scripts written in C#.

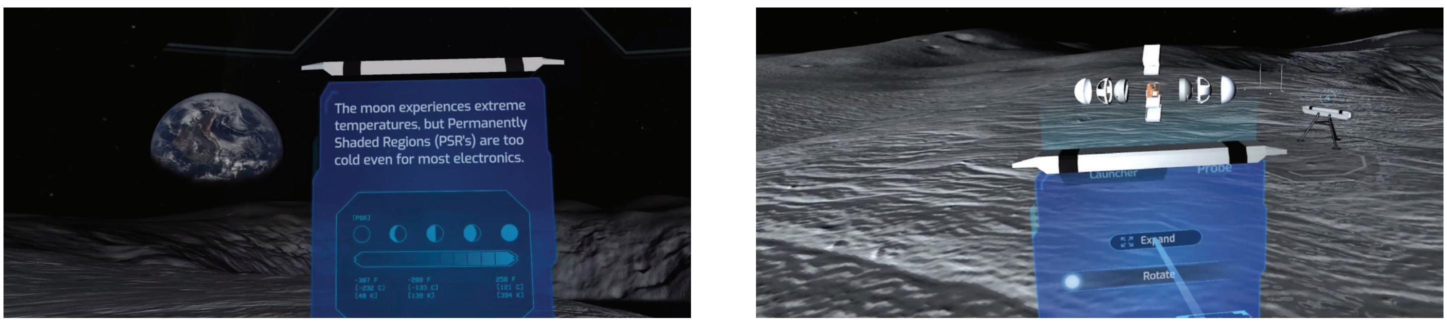


Figure 13. VR environment educational interactions

TECHNICAL SPECIFICATIONS

Total Mass: 15.3 kg
- **Launcher Mass:** 13.9 kg
- **Individual Probe Mass:** 0.35kg (4 probes total)

Total Volume: 0.29 m^3

Power Requirements:
- 12v to 28V
- 7.18 W static, 38.8 W peak

Communications:
- Wifi: 802.11n mesh network

Radiation Protection:
- Electronics are enclosed in High Density Polyethylene (HDPE) enclosures. Current prototypes built with off-the-shelf electronic components but were designed to incorporate rad-hard components for future TRL 5 prototype.

Materials Used:
- Launcher: 6061 T6 Aluminum, 304 Stainless steel, PTFE, PLA (as stand-in for HDPE to be replaced at a later date), Polystyrene (as stand-in for aluminum sheet metal enclosure), carbon fiber tubes, spring steel, Plain carbon steel (as stand-in for stainless steel).
- Probe: 6061 T6 Aluminum, 304 Stainless steel, HDPE, RVC Carbon foam, MLI with Beta Cloth sleeve on exterior, Kapton tape, pressure sensitive tape.

PROOF-OF-CONCEPT TESTING ON EARTH

VELOS subsystem testing was completed to demonstrate the ability to perform its function and further its technology readiness level through laboratory and environment testing. The whole system was tested to demonstrate and validate the functionality of the system and the proof-of-concept.

Testing was conducted in the ASU Interplanetary Initiative Lab (II Lab) which is a multi-use facility to enable student-based space and exploration projects at the university. It is the new home to ASU's Phoenix and DORA CubeSat teams and includes equipment such as vacuum chamber, thermal testing, and clean room. The ASU II Lab was scheduled to open in Summer 2020 but due to COVID-19 pandemic shutdowns and unforeseen issues such as equipment lead time delays, the official opening date was significantly delayed. Due to this delay, the testing equipment (thermal-vacuum chamber, clean room, shaker table) that were intended on being used were only partially implemented and very delayed causing significant testing delays and reduction in testing capability. For example, the thermal-vacuum chamber was intended to be available by mid-summer but due to unforeseen delays, it did not become officially available until mid October and the thermal system was delayed until December. These challenges were mitigated by utilizing the equipment that was available to the team and developing alternative methods for thermal testing for evaluating the performance of the components and for validation of simulations conducted in-lieu of testing.

Launcher testing was conducted in the ASU Drone Studio which is a multi-use space that includes 10,000 sq.ft with 23ft ceilings and 105 high resolution Opti-track motion capture cameras. This space was utilized because it allowed for <0.5mm accuracy object tracking and indoor testing. The ASU Drone Studio was used as an alternative to outdoor launch testing because it provided an indoor facility for testing during Arizona's hot summer months (May - October).

Testing was conducted according to the safety plan and procedures proposed in the Mid-Project report. Testing was conducted by trained lab manager personnel. Students who were present during testing received training which permitted them to assist with testing. In addition, the team followed ASU COVID-19 guidelines and as a result there were no reported cases of COVID-19 on the team.

PROBE TESTING

Vacuum Chamber Testing

Vacuum testing was conducted in the ASU Interplanetary Initiative Lab. The vacuum chamber had an internal volume of 1m^3 and through testing was found to have a functional minimum vacuum pressure of 5e-3 Torr. The following tests were performed.

Test Number	Equipment	Minimum Vacuum Pressure [torr]	Duration [hours]	Outcomes
1	Probe electronics and battery	0.55	0.75	Successful data collection
2	Probe electronics and battery	9e-3	1.85	Successful data collection
3	Probe complete assembly w/ MLI	6.5e-3	3.5	Successful data collection

Table 1. Probe vacuum testing at ambient temperature

The electronics were the primary component that required vacuum testing in the probe subsystem and were the first components tested. In Test #1 the electronics were tested using the vacuum roughing pump which was able to reach a pressure of 0.55 torr during a 45 minute test.

Following the successful completion of Test #1, the electronics were tested in vacuum using the turbo-molecular pump which was able to achieve a pressure of 9e-3 Torr during a test lasting 1.85 hours. During these tests, the onboard temperature sensor was monitored for temperatures that exceed the recommended operating temperatures of the device. The temperature data from Test 1 and Test 2 is shown in Figure 14 below. The inflection point at 50 minutes in Test 2 is the vacuum chamber switching from roughing pump to turbo-molecular pump. Following these tests, the battery was evaluated to determine if any swelling had occurred. Minimal change of 0.1mm or 0.83% in the thickness of the battery was observed after undergoing two weeks of testing.

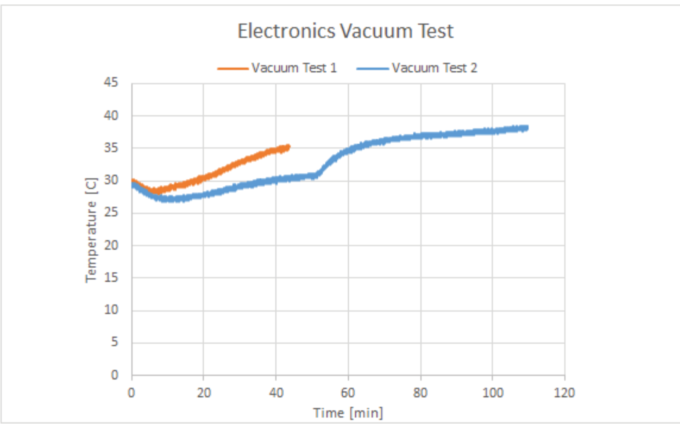


Figure 14. Temperature data from onboard sensor during vacuum tests at ambient temperature

Following the successful completion of Test #2, a vacuum test of the entire probe assembly including MLI was conducted. In this test, the vacuum was run for 3.5 hours and the vacuum pressure reached 6.5e-3 Torr. During this test, the internal sensors were monitored for temperatures exceeding the maximum rated temperature of the electronics and battery. The temperatures from the internal and external sensors were plotted in Figure 15. The inflection point in the temperature around 60 minutes is the vacuum chamber switching from roughing pump to turbo-molecular pump. It can be seen that the internal temperature of the probe steadily increases due to the MLI insulating the heat released from the PCB components. The MLI blankets tested were optimized for operation within the PSR. From preliminary data and simulations, minor modifications to the number of MLI layers could be made to optimize the probes that are intended to operate in the sunlit regions or operate in polar or non-polar regions as specified by the science mission.

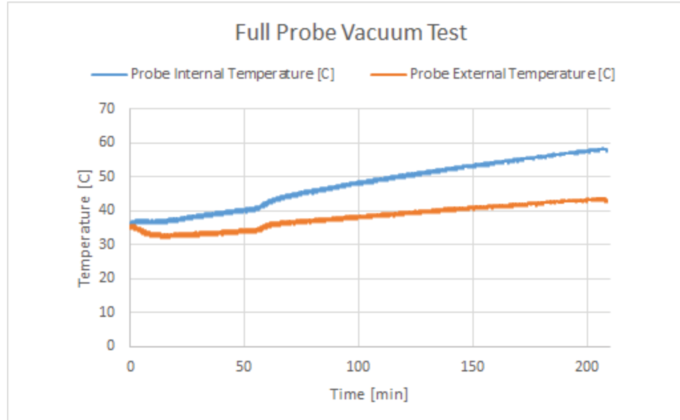


Figure 15. Temperature data from internal and external temperature sensors on the probe during vacuum test at ambient temperature

Thermal Testing

Thermal testing was performed both at ambient pressure and vacuum pressure using Liquid Nitrogen as a cooling agent. Three tests were performed on the probe as shown in the table below. During these tests, internal and external temperatures were being monitored on the probe. Following the tests, the electronics and mechanical hardware were inspected for any noticeable damage.

Test	Equipment	Minimum Probe Surface Temperature [C]	Minimum Pressure [Torr]	Duratio n [hours]	Outcomes
Thermal Only	Probe complete assembly w/ MLI	-163	Ambient	0.9	Successful operation until minimum temperature reached
Thermal Vacuum 1	Probe complete assembly w/ MLI	-68	2e-2	2	Successful operation
Thermal Vacuum 2	Probe complete assembly w/ MLI	-130	1e-2	2	Successful operation

Table 2. Probe Thermal testing

In the Thermal Only test, an insulated box was used to hold LN2 and cool a stainless steel container that isolated the probe from the LN2 with a copper mesh basket cradling and conducting to the probe. Wifi connection was established to the probe to read the internal temperature of the probe PCB and two thermocouples were attached to the exterior of the probe to measure the temperature at the exterior top and bottom. During this test, the temperature inside the probe and outside the probe were monitored and the test was performed until the temperature inside the probe reached the minimum operating temperature.

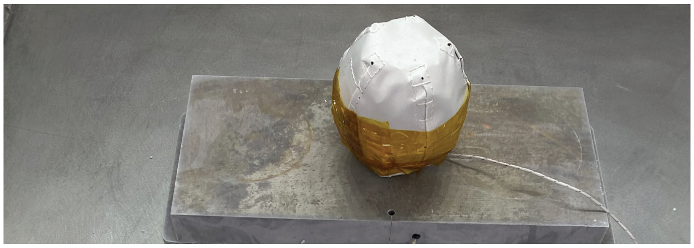


Figure 16. Probe in thermal-vacuum chamber (right)

Thermal-Vacuum Test 1 was conducted in the vacuum chamber to achieve a more realistic environmental testing condition. Because the thermal system for the vacuum chamber was not operational, the team developed an alternative solution which was to cool plates of steel using LN2 and use them as cold plates in the vacuum chamber to serve as a thermal sink. The probe was then placed on a copper mesh basket to serve as a conductor to the cold plate. The temperature inside the probe and the bottom external surface were monitored and the chamber was evacuated to 2e-2 Torr. In Figure 17 below, the temperature inside of the probe maintained a steady state temperature of 28 C once the vacuum chamber pressure was below 5e-2 Torr and the electronics successfully maintained a steady temperature and were able to broadcast data over wifi. From this test, it was seen that the temperature on the external surface of the probe was between -69C and -65C for the duration of the test.

In Thermal-Vacuum Test 2, the copper basket was removed and the probe was placed directly on the cold plate to provide a more effective conduction path to the cold plate. In this test, the internal temperature and external temperature of the probe were monitored

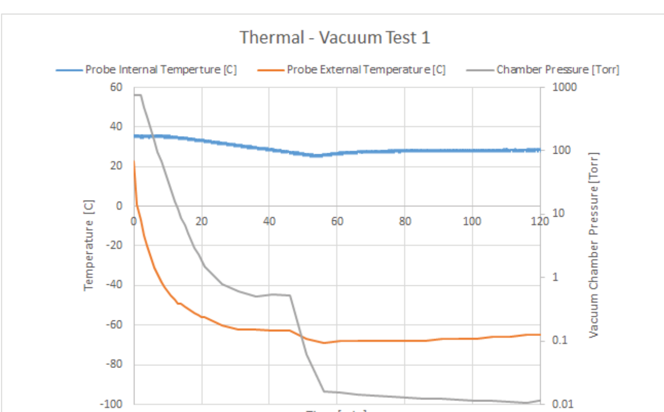


Figure 17.Temperature data during in thermal-vacuum test #1

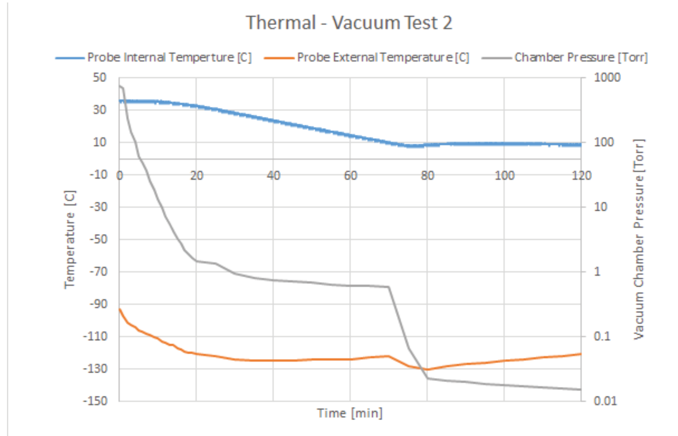


Figure 18. Temperature data during in thermal-vacuum test

as well as the temperature of the cold plate. This test was conducted as a repeat of Thermal Vacuum Test 1 to achieve a lower surface testing temperature of the probe while in vacuum.

The outcome of this test was successful as the probe was able to maintain an internal temperature of 10C while in a partial thermal-vacuum environment with no additional heating. These tests were performed without the probe's onboard heater. The temperature inside the probe was maintained from the heat dissipation from the microcontroller and wifi radio. From these two tests it can be seen that the probe is able to maintain a 100-140C temperature difference between the surface temperature and the internal temperature of the probe using only the heat dissipated from the electrical components.

Once completed, data collected from the thermal vacuum test was used to validate a simulated model. The data collected on the surface of the probe was used as a boundary condition in this model and the results measured by the internal probe sensor were compared with those of the simulation. Additionally, convection was applied to both the outside of the probe and the inside of the electronics casing for the first 1.3 hours of the test. This was done to account for the period of time that a significant amount of air would be present in the probe while the vacuum chamber was decreasing in pressure. Finally, an adjusted coefficient for the thermal conductivity was used for the RVC carbon foam material in order to account for the conduction of air within the pores of the material. The results from the simulation are compared to that of Thermal-Vacuum Test 2 and are shown in Figure 19 below.

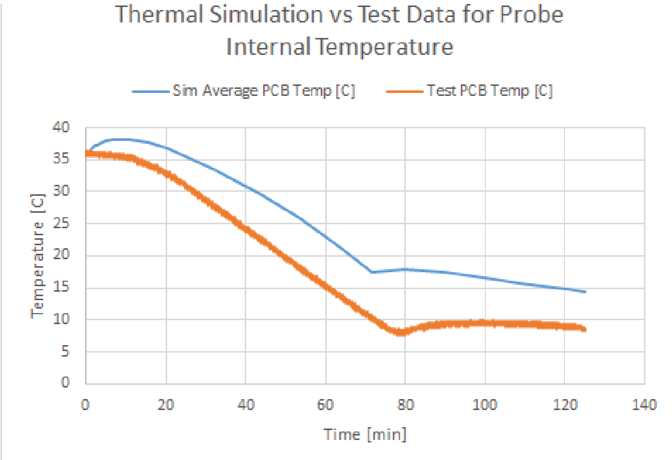


Figure 19: Comparison of simulated and tested PCB temperatures

In Figure 19 the response of the system was seen to change drastically around 1.3 hours when the turbo pump in the vacuum chamber was initiated and the chamber approached a vacuum environment removing most of the air molecules and subsequently convection. Most of the error in the simulation was due to additional uncaptured effects of the presence of air in the physical environment. This test helped to validate the accuracy of the thermal simulation which could then be used to determine the lifespan of the probe in a lunar PSR environment.

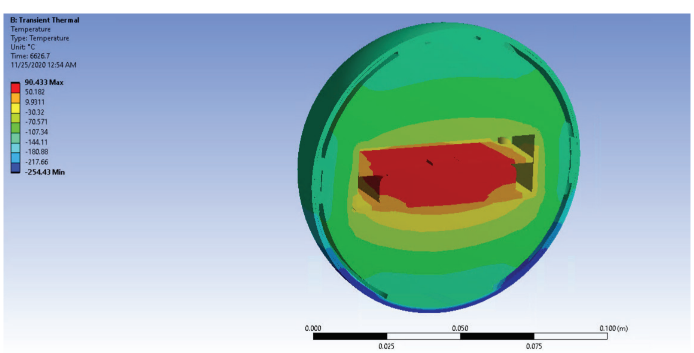


Figure 20: Temperature Distribution of Probe Cross-Section After 3 Hours in PSR

Using the validated simulation model from the physical thermal vacuum test, an ANSYS transient simulation was run to model the temperature and lifespan of the probe once on the lunar surface in a PSR. This model assumed an initial probe temperature of 36 C and an ambient temperature of -237.85 C. The results of this simulation can be seen in Figure 21 which shows the average PCB temperatures over time for varying levels of heating from the onboard heater (0W, 0.25W, 1W, 2W).

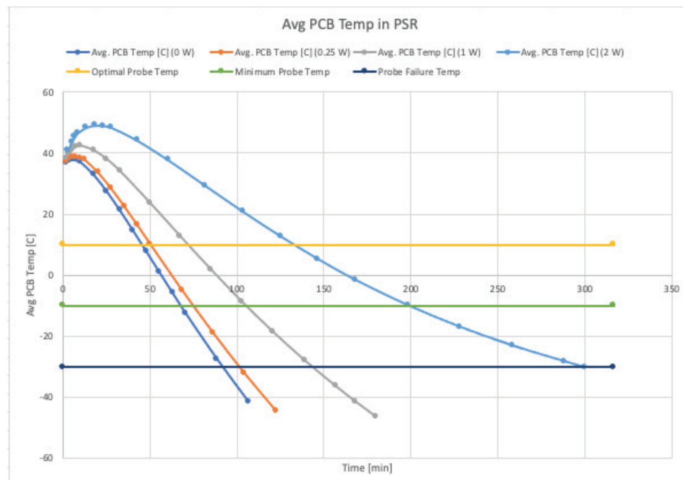


Figure 21. Effect of Heater on Probe Lifespan

The electronics inside the probe are expected to function at normal levels while a temperature greater than 10 C is maintained. Any temperature less than this will result in degraded battery performance and ultimately failure around -30 C. This model shows that the probe operating the 2W heater as designed will be able to sustain an ideal operating temperature for 2.2 hours, between 2.2 and 3.3 hours the probe will maintain operation in its minimum temperature operating range, and once the probe reaches 5 hours, it will have reached its critical failure temperature.

Drop Testing (Simulation)

Drop testing was performed in simulation using ANSYS Explicit simulation software. The probe was designed such that the outer shell and the energy absorption material would plastically deform during impact while the sensor electronics would be protected. Due to the limited quantity of probes that the team could manufacture, ANSYS Explicit was used in-lieu of physical drop testing to eliminate damage to the probe.

The drop test velocity was set as the calculated exit velocity of 12.72m/s of the probe (see Calculations in Appendix). This was deemed as a worse case scenario because this would only occur if the probe impacted the regolith directly such that the velocity vector was normal to the surface of impact. In many conditions, the velocity vector will be at some incidence angle to the surface thereby reducing the normal component of the velocity.

The first drop test simulation was done to compare dropping the probe from a height of 1.67m onto concrete surface, sand based surface, and compared with a theoretical calculation using the drop-shock half sine approximation for concrete. From this comparison it can be seen that the simulation follows the theoretical results closely.

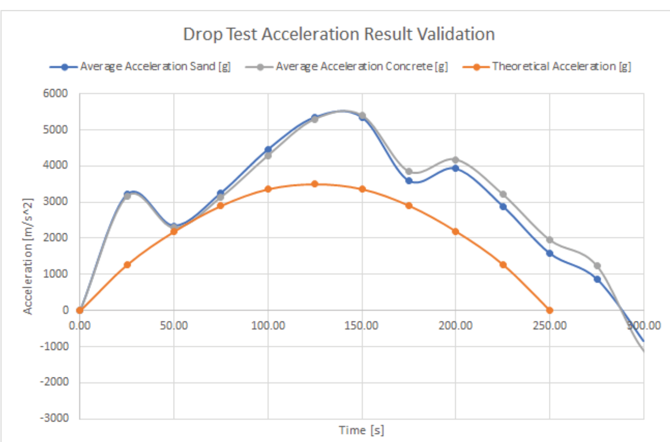


Figure 22. Validation of Drop Test Simulation Model

Once this simulation was complete, the drop test was completed with the probe traveling at a velocity of 12.72 m/s impacting sand. From the results in Figure 23, it can be seen that the acceleration on the probe shell first spikes when the probe hits the surface and then there is a delay before the acceleration of the enclosure spikes. This is due to the energy absorbing foam that helps protect the electronics during impact.

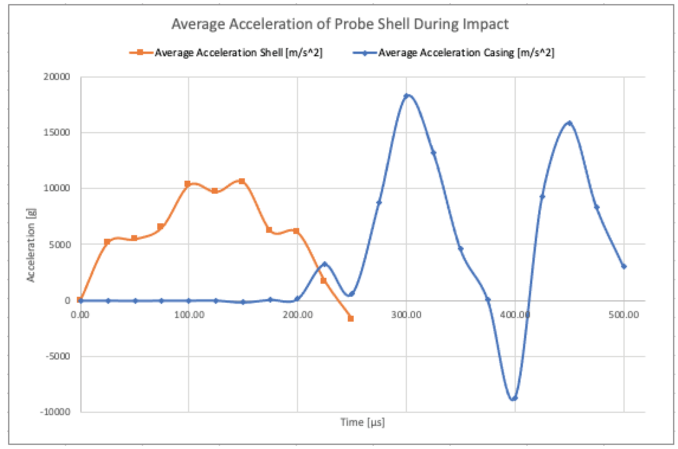


Figure 23. Shell and PCB Enclosure Acceleration Results

The accelerations were used to run a structural analysis of the probe shell. From the results in Figure 24 below it can be seen that max equivalent stress is 2.342e8 Pa which is above the ultimate strength of aluminum meaning that under worse case launch conditions into a solid surface, this shell will yield and sustain damage at the point of maximum stress. This is consistent with the design intent of the shell which was to only provide a rigid outer shell to protect the electronics within.

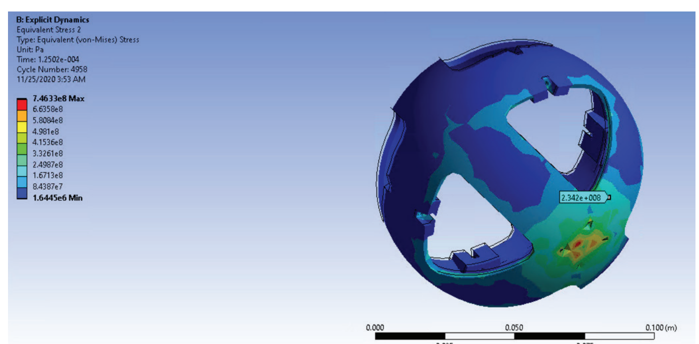


Figure 24. Stress Distribution in Shell at Peak of Impact

Communications Systems Testing

The wifi mesh network testing consisted of three separate tests. In the VELOS mesh network, the launcher is the root node and the probes are leaf nodes of the network. The first test conducted was full mesh network communication. In this test, three nodes (1 root and two leaf nodes) were placed in the ASU Drone Studio and allowed to establish a successful network and transmit data.

Once the basic mesh network test was complete, the second test was conducted to evaluate node connection speeds. Once the network was established the nodes were placed in a faraday cage to shield the wifi signal to simulate them disconnecting from the root node network. Once they had disconnected, the nodes were taken out of the faraday cage and allowed to reconnect. This reconnection was timed at 12s.

After the node connection test, the node mesh multi-hop test was conducted. This test was conducted to confirm the data transmission rates that could be achieved by an orphan node in the network that can temporarily see the relay node as it is launched. This test was conducted by isolating a node in a faraday cage and moving it far from the root such that it could not establish a connection. The intermediate node (relay probe) was placed in a position that would allow it to connect to both the root and the orphan node and it was placed in a faraday cage. At the start of the test, the relay node was removed from the faraday cage and allowed to establish connection with the root and the orphan. This connection and data transmission rate were timed at 5 seconds indicating successful completion of the data transmission within the 15.5 second window of opportunity calculated for the relay probe.

Test	Description	Outcome
Basic Mesh Network	Network established	Nodes connected to root and able to transmit data at a rate of 1Hz
Node Connection Test	Leaf nodes disconnected from root and reconnected	Successful reconnection and data transfer in 12 seconds
Node Mesh Multi-Hop Test	One node is missing from the network and then establishes a connection with another node that can see the root.	Successful reconnection and data transfer in 5 seconds

Table 3. Mesh networking testing results

LAUNCHER TESTING

The VELOS launcher was designed to deliver probes into the PSR from a maximum range of 100m and collect the data wirelessly from the probes. To achieve this, the launcher was designed to actuate in the altitude and azimuth axis to a position specified from the lander and then launch each probe sequentially. Once the probes are in the field, it collects data from each probe and stores it before transferring it back to the lander for transmission to Earth. This concept of operations was designed to minimize risk by reducing the number of actuators and moving components in the system. The launcher testing focused on the core functionality of the launcher to actuate, launch, and communicate.

One of the biggest challenges in testing the launcher was finding the correct spring and release mechanism to achieve the launch distance needed. The release mechanism used was a stand in for a flight ready TiNi™ Frangibolt™ hold-down release mechanism (HDRM) from Ensign-Bickford's TiNi Aerospace line of components which specialize in electric HDRMs. The cost and availability of acquiring a Frangibolt was not within the scope of the budget due to the high cost of the device and the cost of each single use bolt which is custom machined. The team opted to use a method proposed by Thurn et al. [2]. The design was proposed as a low cost and easy to use release mechanism that uses a piece of vectran cord as the hold mechanism and a nichrome wire as the cutter mechanism. Although this allowed the team to run repeated tests at a low cost, it required a significant amount of iterative design and testing to find a cord material that was strong enough and small enough to be cut efficiently with a nichrome wire.

To conduct testing safely, the team followed the testing safety plan to minimize risk of system failure by testing various springs and release mechanisms starting from light springs to test the operation of the system and moving to heavier springs which could provide sufficient force to launch the probe the required distance. Each increase in spring rate required minor iterative modifications to the release mechanism, the plunger mechanism, and the spring compression system. Through this testing, the team was able to reach the desired launch distance of over 16.5m which is equivalent to over 100m on the lunar surface. (see calculations in Appendix).

Actuation Testing

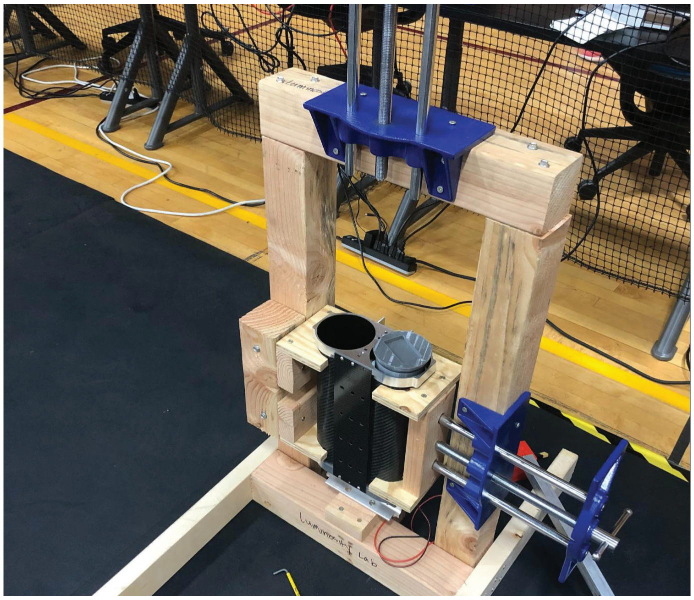
Actuation testing was performed using the launcher onboard PCB which allows for wired or wireless communications. The launcher actuation was tested with both wired and wireless communications methods. The launcher's actuators were tested under full load for rotation in the azimuth and altitude axis as well as for actuation of the nichrome release mechanism for launching the probes. See Proof-of-Concept video for full actuation of the launcher.

Figure 25. Launcher actuation in the azimuth axis

Launch Testing

Launch testing was conducted to test the system's ability to deploy the probe a distance of 16.5m. This was achieved through testing of various springs to evaluate the mechanical strength and resilience of the launcher under load. The basic launch testing procedure is outlined below.

- The launcher was fastened to a 1.3x1.8m table at a height of ~0.8m.
- The launch tubes for one side of the launcher were removed from the base.
- The launch tubes were placed into the custom compression device designed to safely compress the spring.



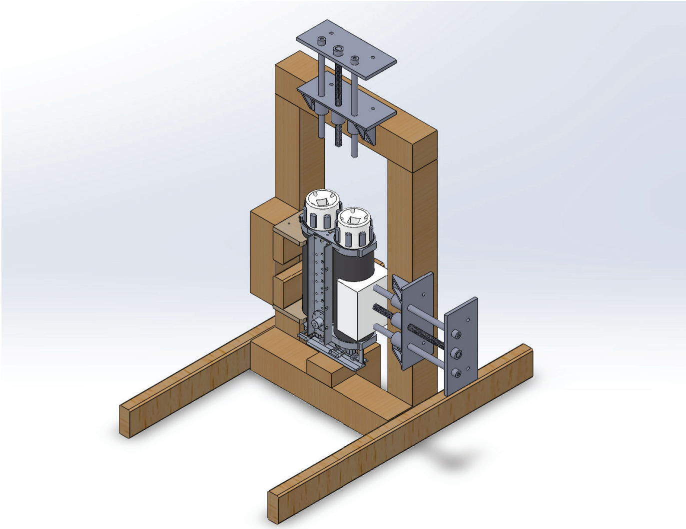


Figure 26. Custom Spring Compression Device

- Once the spring was fully compressed in the tube, the release mechanism was attached to the backplate of the launch tubes and the tubes were removed from the compression device.
- A safety plate was fastened to the end of the tubes until the tubes were ready for launch.
- The tubes were then attached to the base and prepared for launch.
- The safety plate was then removed and a weighted probe stand in was placed in the launch tube.
- Cameras were then placed to capture both slow motion of the launch tubes and to capture the probe launch distance.

Over the course of 22 test launches, the team was able to achieve the goal distance of 16.5m from launcher to impact with the ground plane. Note: the total distance recorded was the distance from the launcher to the first impact, it didn't not include rolling distance. In Figure 27 below, the launch distance achieved from each test is plotted. After each test, the data were reviewed and modifications proposed to improve the performance.

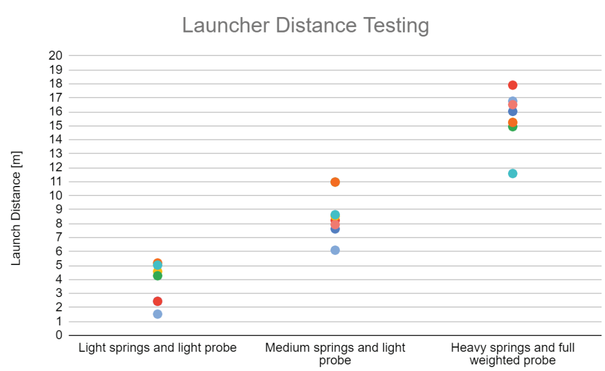


Figure 27. Launch distance (from launcher to impact with ground plane) vs. test over the course of 8 weeks of testing

Early tests were conducted with plastic stand-in's for the probe weighing roughly 42 grams. Light springs and probes were used for early testing as the team optimized the launcher for heavier springs. Figure 27 shows the launch distance from each test as a function of the spring rate. The light class of springs had a spring rate that corresponded to roughly 30-50lbs load at maximum compression, the medium spring rate corresponded to roughly 100-150 lbs load at maximum compression, and the heavy spring rate corresponded to 350-400 lbs at maximum

Spring Class	Spring Rates[N/m]
Light	3000-4000
Medium	6000-8000
Heavy	10000-12000

Table 4. Spring rate for springs tested

compression. The final spring that was able to achieve a launch distance of 16.5m for a probe weighing 350g was equal to 12200 N/m.

Vacuum Chamber Testing

The launcher subsystem was tested in vacuum to gauge the performance of the current design in a vacuum environment. For this test, the launcher was placed in the vacuum chamber with a portable battery. The vacuum chamber was run to a minimum pressure of 6.5e-3 Torr for 3.5 hours. During this test, the launcher actuation was tested in vacuum 1 hour after starting the test. At 3.5 hours, the launcher PCB was checked and was found to be operational. Following the test, the launcher was inspected for damage and it was found that all systems were still functional following the vacuum test.

Structural, Shock, and Vibration Testing (Simulation)

The launcher was simulated using static structural analysis and a modal and random vibrations simulation in accordance with NASA NTSS GEVS specifications [3]. The static structural analysis was completed to better understand the deformations that occur in the launch tubes during launch testing. The simulation shows the shaft deformation causes a relative motion in the barrel of the launch tube of roughly 2cm. This deformation was also observed in launch testing. In addition, the reaction forces and moments were calculated from the simulation. The maximum component of the reaction force on the base of the launcher was found to be 1394.8 N (313.6 lbf) and the maximum component of the reaction moment was found to be 337.0 N*m (2982.7 lbf*in). This information will be used for development to further reduce deformation in future prototypes.

In addition, a modal and random vibrations analysis was conducted on the launcher. This test was used to determine the critical components in the assembly that need to be evaluated prior to TRL 5 Shock/ Vibrations testing. From this analysis it was found that the tube shaft was a critical component that needs to be updated prior to physical testing. The current shaft design serves as a proof of concept and with minor modifications needing to be made to increase rigidity and strength for TRL advacement.

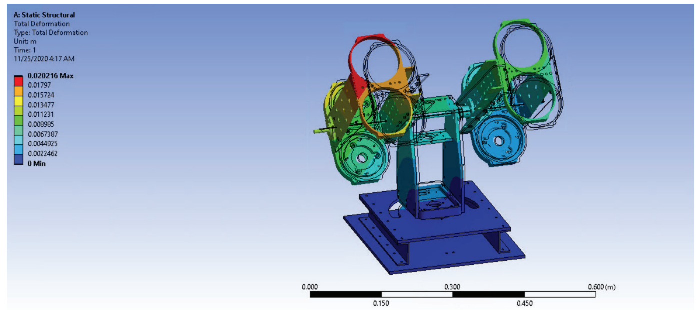


Figure 28: Deformation of Launcher Under Spring Load

FINAL PROOF-OF-CONCEPT LAUNCH TESTING

Final proof-of-concept launch testing was conducted to show full operation of the system in a realistic launch scenario and to test the probes under full launch loads. The test was designed to show the proof of concept of launcher actuation, probe deployment, and probe data collection. To accomplish this, the launcher was mounted to a table ~0.8m off of the ground and two out of the four launch tubes were prepped for testing. The test was designed so that one probe would be launched at the maximum distance of 16.5m (100m on the Moon) and the other probe would be launched at a distance of 7.9m (44m on the Moon). Each probe would be launched at different altitudes and headings to show the launcher actuation. Upon impact, the probes made contact with a hard wood floor covered with slip resistant hard rubber in the testing lab. The ground surface of the testing lab was not altered from its original state for this test. Following the launch, the probes were monitored for successful data collection and wireless communication with an external data logging computer.

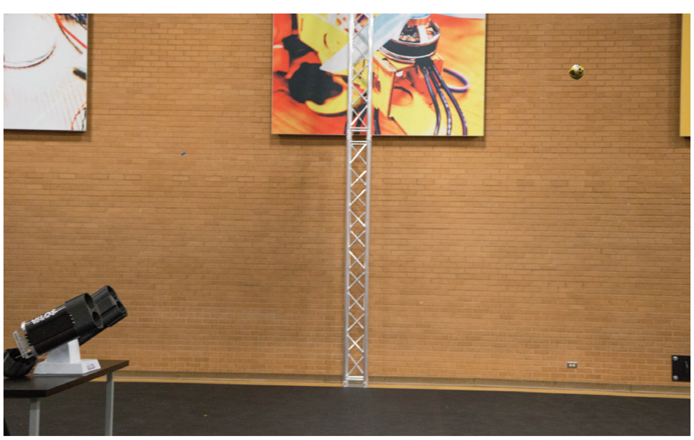


Figure 29. Launcher and probe mid-air during launch

Internal acceleration data was recorded locally to the ESP32's internal flash storage. The probe sampled X, Y, and Z acceleration as well as temperature in degrees C for proof of concept. To minimize stored data, the software onboard the probe constantly monitored the change in acceleration acting on the probe, and when the value exceeded a set threshold, the probe would begin logging. This threshold was set such that the probe would not begin collecting data until launched. After 1000 samples were collected, the software would discontinue sampling and store data to be remotely accessed by a PC. In Figure 30 below, the acceleration magnitude is plotted in G's during the first 3 seconds after launch. In this short time frame, the initial acceleration due to the launch can be seen. In addition the internal temperature was successfully recorded and the average was found to be 33.2C.

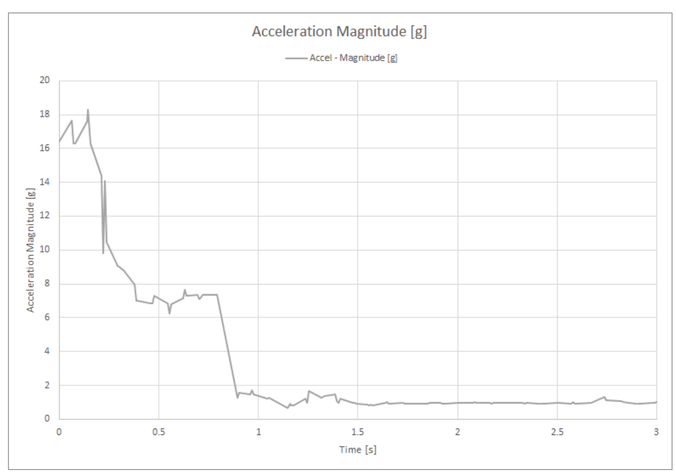


Figure 30. Internal IMU Acceleration Magnitude: Launch 2

PATH TO FLIGHT

The goal of VELOS is to provide a solution for early exploration via the Artemis program and beyond. The BIG Idea 2020 Challenge helped launch this vision and has provided the first step toward the goal of reaching the Moon. VELOS was designed to include flight certified hardware or choose an alternative to flight hardware for initial prototyping as well as minimize design decisions that did not enable a flight ready prototype in the future. Hardware that needs to be replaced with flight certified hardware are: hold-down release mechanism, probe wifi radios, launcher wifi radio, launcher tube shaft, launcher plunger, launcher motors, external radiation and thermal shielding for the launcher.

In addition, VELOS was designed such minimal modifications would need to be made for maximum flight safety. This includes the ability for electronic pin-puller mechanism to be incorporated into the turret to secure it during flight, electronic separation bolts to hold safety caps on the launch tubes, and the ability for the launch tubes to point vertically downward into base such that the base would provide a redundant containment mechanism for the launch tubes.

By completing the BIG Idea Challenge, the VELOS subsystems are TRL 4 with minimal updates needed to achieve TRL 5. Each component has been tested in a laboratory environment and some components have been tested in a partial relevant environment. The next goal for VELOS is to make the minor design revisions needed to replace non-flight ready components with flight ready alternatives followed by testing all components in a certified relevant environment to fully reach TRL 5. The team has been in contact with NTS Testing Services to evaluate the systems specific testing needs to reach TRL 5. The VELOS team intends to continue developing this system and is actively submitting proposals to future calls and challenges that will continue to enable TRL advancement.

RESULTS/CONCLUSION

VELOS was designed to provide a reliable, versatile, and scalable system for exploration in extreme environments. Over the course of this project, the VELOS team has designed, built, and tested the system to achieve its proposed objective which was to launch a sensor probe over 100m on the lunar surface into the PSR and relay data back to the launcher. The critical components of this system were to design a launcher that could successfully launch the probe over 100m and to design a probe that could carry a small sensor payload and be deployed in the PSR. The Proof-of-Concept test video combined with the collected data from testing each subsystem indicates that the prototype designed achieves this goal.

Through testing and simulation, each VELOS subsystem was proven in a laboratory environment and partial relative environment allowing VELOS to achieve TRL 4 with progress toward TRL 5. From the launcher distance testing, it was shown that the proposed design could launch a 350g projectile over 16.5m on Earth which equates to 100m on the lunar surface at variable distances and positions. During final proof-of-concept testing, one probe was successfully deployed over 16.5m and one probe was deployed 7.9m at roughly 30 degrees heading from the first deployment to show variable deployment capability. Both probes launched were able to sustain operation after impact and collect accelerometer and temperature data during the test. From the probe thermal-vacuum chamber testing, it was shown that the probe electronics could sustain operation at a temperature of -120C and a vacuum pressure of 2.2e-2 Torr with the thermal blankets designed. From the probe communications testing, it was shown that an isolated probe that is disconnected from the mesh network can quickly connect and sync data within 15 seconds to relay information back to the launcher in the event of loss of line-of-sight.

The first step in the Scientific Method is “make an observation”. VELOS - Variable Exploratory Lunar Observation System takes this step by providing a solution that can be used by scientists or students for future exploration on the Moon, Mars, and beyond.

![VELOS]

DETAILED TIMELINE

Task	Task	Month / Week	Number of students	Student H
1	Detailed Design			
	1.1	Mechanical systems design	3	180
	1.2	Electrical systems design	3	180
	1.3	Communications systems design	2	80
2	Detailed Design Prototyping and Testing			
	2.1	Mechanical systems prototype test	3	90
	2.2	Electrical systems prototype test	3	90
3	Design Optimization			
	3.1	Mechanical systems optimization/redesign	3	225
	3.2	Electrical systems optimization/redesign	3	225
	3.3	Communications system optimization	2	100
4	Design Optimization Prototyping			
	4.1	Mechanical systems prototype manufacturing: cnc , water jet, and 3D printin	3	135
	4.2	Electrical systems protoype manufacturing: professional pcb manufacturing	3	135
	4.3	Communications system prototype: mesh network bench testing	2	60
5	Mid-Project Report (5 pg)		8	150
6	Design Optimization Proof of Concept Testing			
	6.1	Launcher systems testing	3	90
	6.2	PCB bench testing	3	45
	6.2	Mechanical fit test	2	40
7	Mid-Project Report Pass/Fail			
8	Design for Manufacturing			
	8.1	Mechanical systems DFM	3	120
	8.2	Electrical systems DFM	4	160
9	Development, Design Optimization and Testing			
	9.1	Mechanical systems manufacturing: probe manufacturing, minor turret manu	3	120
	9.2	Electrical systems menufacturing: launcher PCB, probe PCB manufacturing	4	160
	9.3	Launcher systems design optimization testing		100
	9.4	Probe systems design optimization testing		60
10	Final Proof-of-Concept Testing			
	10.1	Probe thermal-vacuum testing at liquid nitrogen temperatures	4	80
	10.3	Communications mesh network testing, coms relay testing	2	240
	10.4	Launcher systems operation testing	3	80
	10.5	Full systems launch testing of turret, probe, communications systems	8	160
11	Technical Paper & Proof-of-Concept Demo		6	320
12	Oral Presentation		6	120
13	Poster Presentation		6	120
		Key		

Months: Feb, Mar, April, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec, Jan (weeks 1 2 3 4 each)

Key: Design, Manufacturing, Testing, Reporting

DETAILED BUDGET

Cost Categories	Total Budget 2/17/2020 10/12/2020	Budget Installment 1	EXPENSES As of 10/31/20	Budget Installment 2	EXPENSES As of 11/20/20
Senior/Key Personnel:	**$6,201**	**$6,201**		**$0**	
Tyler Smith	$4,500	$4,500			
ERE:	$1,701	$1,701			
Effort (FTE Months; AY/SUM/CAL):	0/0/0.6	0/0/0.6		0/0/0.6	
James Bell	$0	$0			
ERE:	$0	$0			
Effort (FTE Months; AY/SUM/CAL):	0/0/0	0/0/0		0/0/0.3	
Other Personnel:	**$32,590**	**$5,262**		**$27,328**	
Undergraduate Student TBD03	$32,225	$5,203		$27,022	
ERE:	$364	$59		$305	
Effort (FTE Months; AY/SUM/CAL):	0/3/3			0/3/3	
Total Number Other Personnel	3			3	
Total Salary, Wages and ERE:	**$38,791**	**$11,463**	**$11,463**	**$27,328**	**$27,328**
Equipment:	**$0**	**$0**		0	
Travel:	**$0**	$0		**$0**	
1. Travel for 5 to Onsite Forum	$0	**$0**		$0	
Other Direct Costs:	**$24,618**	$17,618		$7,000	
1. Materials and Supplies	$17,618	$17,618	$15,544		
2. Equipment or Facility Rentals/User Fees	$2,000			$2,000	$737
3. Testing Costs	$5,000			$5,000	$2,395
Direct Costs:	**$63,408**	**$29,081**	**$27,007**	**$34,328**	**$30,460**
Indirect Costs:	**$20,925**	**$9,597**	**$9,597**	**$11,328**	**$11,328**
Total Direct and Indirect Costs:	**$84,333**	**$38,677**	**$36,604**	**$45,656**	**$41,788**

Please note that due COVID19 NASA has allowed an extension on the use of budget funds. In addition ASU's accounting system is generally 30-60 in posting expenses and payroll redistributions.

APPENDIX

Calculations

Calculations implemented in Matlab and Excel

Projectile Motion Equations [4]

X-position: $xt = x_0 + v_{0x}t$
Y-position: $yt = y_0 + V_{0y}t + 1/2gt^2$
X-velocity: $V_x = V_{0x}$
Y-velocity: $V_{yt} = V_{0y} + gt$
Velocity Vector Magnitude: $V = \sqrt{V_x{}^2 + V_y{}^2}$

For launch angle of 45 degrees, launch distance of 100m, gravity of 1.62m/s^2

- Initial velocity (launch velocity): 12.72 m/s

For launch angle of 45 degrees, exit velocity of 12.72m/s, gravity of 9.81m/s^2

- Launch distance: 16.5m

For maximum flight duration during communications relay mode, velocity = 12.72, angle = 85 degrees, gravity = 1.62 m/s

- Flight time: 15.5s, launch distance: 17.3m

Conservation of Energy Equations [5]
The spring needs to accelerate the probe from 0-12.72m/s to achieve a launch distance of 100m on the Moon or 16.5m on Earth. The spring energy needed can be calculated with conservation of energy equations.

Spring Potential Energy: $1/2\,kx^2$, k is the spring constant, x is the spring compression
Kinetic Energy: $1/2\,mV^2$, m is the mass of the object, V is the velocity

In the simplified case that all potential energy is converted to kinetic energy and exit velocity is 12.72m/s:

- kx^2 = 56.62 Nm, The final tested spring has a suggested max kx^2 =74 Nm.

References

[1] Narici, L., Casolino, M., Di Fino, L. et al. Performances of Kevlar and Polyethylene as radiation shielding on-board the International Space Station in high latitude radiation environment. Sci Rep 7, 1644 (2017). https://doi.org/10.1038/s41598-017-01707-2

[2] A. Thurn, S. Huynh, S. Koss, P. Oppenheimer, S. Butcher, J. Schlater, and P. Hagan, “Proceedings of the 41st Aerospace Mechanisms Symposium, Jet Propulsion Laboratory, May 16-18, 2012,” in A Nichrome Burn Wire Release Mechanism for CubeSats.

[3] GSFC-STD-7000. (2019, April 22). Retrieved November 25, 2020, from https://standards.nasa.gov/standard/gsfc/gsfc-std-7000

[4] Giancoli, Douglas C. Physics: Principles with Applications (7th Edition) - Standalone book. Pearson, 2016.]

[5] Physicsclassroom.com. 2020. Potential Energy. [online] Available at: <https://www.physicsclassroom.com/class/energy/Lesson-1/Potential-Energy> [Accessed 22 November 2020].