The Planetary Science Journal, 6:297 (18pp), 2025 December https://doi.org/10.3847/PSJ/ae0b51

TRIDENT Ice Mining Drill for Lunar Volatile Prospecting for PRIME-1 and VIPER Missions

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Received 2025 May 20; revised 2025 August 14; accepted 2025 September 11; published 2025 December 22

Abstract

The Regolith and Ice Drill for Exploration of New Terrains (TRIDENT) is a 1 m class drill developed for capturing regolith and ice during the Volatiles Investigating Polar Exploration Rover (VIPER) and the Polar Resources Ice Mining Experiment (PRIME-1) lander missions to the south pole of the Moon. The drill employs decoupled rotation and percussion mechanisms to allow for three modes: rotation, percussion, and rotation–percussion, depending on operational goals and the material strength. TRIDENT can be operated in such a way that it can characterize subsurface material and deliver cuttings to the surface for characterization by other instruments. TRIDENT includes a drill-bit-integrated temperature sensor and an auger-integrated heater with a colocated temperature sensor 35 cm above the bit for thermal conductivity measurement. The heater can also be used in cases of ice adherence (freezing in) and to enhance the sublimation of ice from the cuttings pile. TRIDENT collects and delivers subsurface regolith onto the surface using a "bite" sampling approach: cuttings are captured in the auger flutes, the auger is retracted after drilling a 10 cm bite, and then 10 cm worth of cuttings are deposited onto the surface, forming a cuttings cone. This regolith cone is then analyzed by instruments Mass Spectrometer Observing Lunar Operations (MSOLO) and NIRVSS on the VIPER and MSOLO on the PRIME-1 missions. The drilling activity creates a seismic signal that can be detected on any associated inertial measurement unit that is turned on during the activity, which enables seismic science. TRIDENT represents two decades of technology development for planetary applications and could be deployed on any future missions to other solar system bodies. TRIDENT on the PRIME-1 mission has been successfully deployed in horizontal orientation (this orientation was due to the lander being in an off nominal landing orientation). All actuators, sensors, and heaters worked as designed. Even though the drill did not penetrate regolith, it was covered in regolith that fell onto the drill during the landing operation. VIPER is scheduled to launch to the Moon at the end of 2027 on Blue Origin's Mk1 lander.

Unified Astronomy Thesaurus concepts: The Moon (1692)

1. Introduction

The Moon is an airless body primarily covered by a fine, dusty regolith layer. This material covers a layer of coarse bedrock fragments (megaregolith) and the bedrock itself and varies by depth per region. Without an atmosphere or global magnetic field active over geologic timescales, micrometeorites, solar wind, and cosmic radiation constantly bombard the lunar surface at high energies. The outermost dust layer also protects subsurface material from most radiation, creating an environment that is more stable than those exposed to space. Accessing the subsurface allows scientific research to look back in both lunar and solar system time and elucidate the evolution of the Moon, the Earth, and the solar system in general (including the evolution of the Sun). Key scientific investigations are only possible through the acquisition and analysis of subsurface material. Every Apollo mission had astronauts collect subsurface material through astronaut-powered sample tubes and the Apollo Lunar Surface Drill. Soviet Luna 16, 20, and 24 had rotary–percussive coring drills for sample return missions. The first two drills penetrated to just over 20 cm, while Luna 24 reached 2 m depth (Y. Bar-Cohen & K. Zacny 2009). The Chinese landers, Chang'e 5 and 6, included 2 m rotary–percussive drills that penetrated to 1 and 1.5 m, respectively (T. Zhang et al. 2023; Y. Zheng et al. 2023). The two drills are based on the Luna 24 drill architecture.

The Regolith and Ice Drill for Exploration of New Terrains (TRIDENT) is a rotary–percussive ice mining drill developed specifically to access subsurface material for scientific

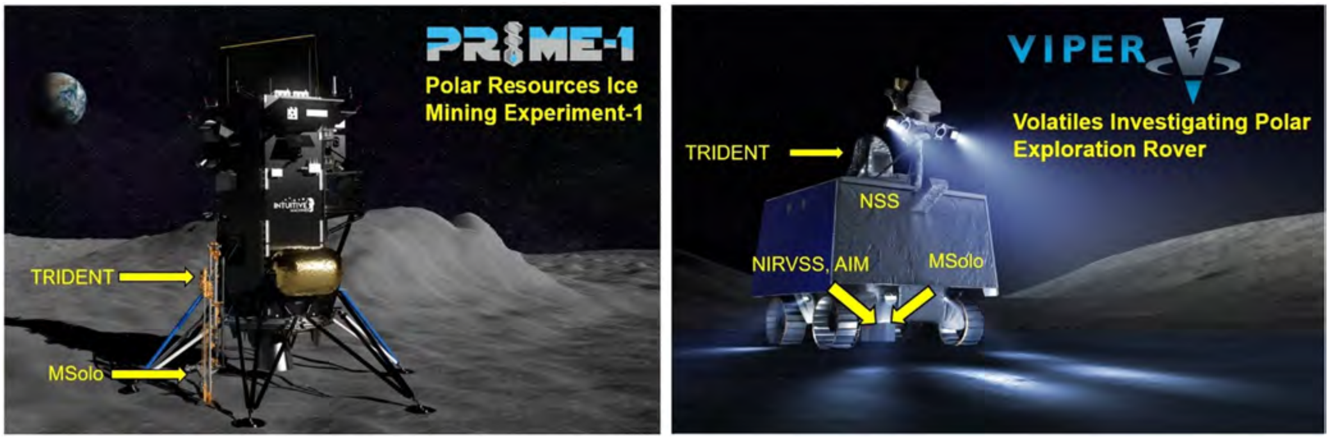

Figure 1. PRIME-1 (left) and VIPER (right) missions to the south pole. TRIDENT is mounted to the side of the lander on the PRIME-1 mission and in the middle of VIPER. The Intuitive Machines IM-2 lunar lander, named Athena, is just over 4 m tall, while VIPER stands approximately 2.5 m tall.

analysis. TRIDENT was developed and two identical units were delivered to be part of two lunar south pole missions: Volatiles Investigating Polar Exploration Rover (VIPER; K. Ennico-Smith et al. 2022) and Polar Resources Ice Mining Experiment (PRIME-1; J. Quinn 2023; K. Zacny & P. Chu 2024) as shown in Figure 1. TRIDENT is designed to be a flexible, low-power option for all lunar robotic missions.

The PRIME-1 mission was part of the Intuitive Machines Nova-C lander, called Athena. It was launched on a SpaceX Falcon 9 from Launch Complex 39A at 00:16:30 UTC on 2025 February 27 and touched down on the lunar surface on March 6 at about 17:30 UT (12:30 EST) at the Mons Mouton plateau close to the south pole. Landing coordinates were 84.°7906S, 29.°1957E. Upon landing, it was discovered that Athena had landed on its side, which prevented the TRIDENT drill from completing its mission. Figure 2 shows two images of the TRIDENT drill on the lander during cruise and its position after landing. After landing, there was sufficient power to operate the TRIDENT drill and test all actuators, mechanisms, and sensors. Over the course of approximately 20 minutes, the drill rotation and percussion actuators were powered on to demonstrate performance of percussion and rotation, the launch locks were released to free up deployment and feed stages, and both stages then were extended to their maximum distance of 35 and 100 cm. In addition, the heater inside the auger was cycled, and data from the two temperature sensors in the drill bit and the auger were acquired. All these operations were performed while the drill mechanism and avionics box were covered in a thick layer of lunar regolith that most likely fell on the drill during landing operation. Upon final review, the TRIDENT system operated flawlessly within the flight parameters.

The VIPER mission is targeting the western edge of the Nobile crater on Mons Mouton (Artemis Candidate Landing Region Leibnitz Beta Plateau, centered at 85.°425S, 31.°722E). VIPER is designed to explore the south pole region and identify ice and other materials for both scientific and in situ resource utilization (ISRU) purposes. The nominal 100 day mission of NASA's VIPER mission would lead to a localized ground-truthing of the planet-wide ice measurements made by orbital assets such as the Moon Mineralogy Mapper (Peters et al. 2009). VIPER has been fully qualified and is ready for launch to the Moon on the next available lander.

These two missions utilize identical drills with no functional differences, aside from a set of calibration targets required for the Near InfraRed Volatiles Spectrometer System (NIRVSS) instrument on the VIPER mission. Due to its complex operations, increased mission lifetime, and the identical nature of the instruments, this paper focuses on the inclusion and operations of TRIDENT on the VIPER mission.

The VIPER mission exploration area is approximately 5×5 km centered at 31.°6218E, 85.°42088S on Mons Mouton. The area includes several permanently shadowed regions where water ice has been inferred to exist from orbital measurements (C. M. Pieters et al. 2009; L. Li et al. 2018; R. Beyer et al. 2025, this issue). The south pole harbors permanently shadowed craters and shallow subsurface areas where water ice and other volatiles are thermodynamically stable over geologic time. Although orbital measurements indicate its presence, ground-truth measurements are necessary to constrain the water's origin, history, and potential for ISRU in these regions. The main goal of the VIPER mission is to understand the physical state and meter-scale distribution of water ice, horizontally and vertically, in these protected environments. Thus, VIPER's payload was chosen to finely map the distribution and concentration of water ice in the near subsurface to a depth of 1 m over its 100 day nominal lifetime. TRIDENT is also designed to make physical measurements of lunar regolith, such as thermal conductivity, to improve inputs to the modeling of ice deposits observed over the entire lunar south pole region.

The VIPER science instrument suite (Figure 3) was designed to provide complementary data that would allow for better understanding of the resource potential of the lunar south pole (J. Captain et al. 2016; A. Colaprete et al. 2020; R. Aguilar-Ayala et al. 2025, this issue). Furthermore, the science operations architecture of the VIPER mission was designed to provide mission-enhancing, real-time collaborative data analysis and science decision-making that would inform TRIDENT drilling locations during surface operations. The Neutron Spectrometer System (NSS) instrument, mounted in front of the rover, is designed to measure thermal and epithermal neutrons, which indicate the presence of water ice. NSS provides water-ice concentration within the top 1 m, particularly estimated burial depth, which can be compared with the "ground truth" of TRIDENT, Mass Spectrometer Observing Lunar Operations (MSOLO), and NIRVSS measurements during the subsurface

Figure 2. The Athena lander in lunar orbit and on the Moon's south pole, as seen from one of its navigation cameras. The TRIDENT drill is to the left of MSOLO (the white rectangle) between the legs of the lander. The TRIDENT avionics box can be seen in the foreground on both images. On the surface image, the TRIDENT avionics box is covered in dust. Note the crescent Earth in the background. Images: Intuitive Machines.

Figure 3. VIPER will include three instruments. From left to right: NSS, NIRVSS, and MSOLO.

assay activity. MSOLO is a mass spectrometer designed to capture volatiles evolving from cuttings delivered to the surface by the TRIDENT drill (J. Captain et al. 2016; J. Kleinhenz et al. 2018; T. Roush et al. 2018; R. Aguilar-Ayala 2023). The NIRVSS instrument is designed to view the cuttings pile generated by the TRIDENT drill and determine the mineralogy and volatile content of the regolith (T. Roush et al. 2016). NIRVSS includes the Ames Imaging Module (AIM), a camera that will take high-resolution images of the cuttings pile. These images are critical in determining the volume of cuttings delivered to the surface, the regolith texture, and the angle of repose of the subsurface material. The rotational speed and torque from rover wheel actuators (E. Rezich et al. 2025, this issue) alongside cameras (R. Beyer et al. 2025, this issue) and inertial measurement units (IMU) can also be used to constrain the geotechnical, geophysical, and terramechanical properties of the regolith, complementing some of TRIDENT's investigations. Additionally, the VIPER Visible Imaging System is comprised of eight cameras (the Navigation Cameras stereo pair mounted on the mast gimbal, the AftCam stereo pair mounted on the aft panel, and four HazCams mounted in the wheel wells) that capture gray-scale visible-wavelength images of the lunar environment and the rover's upper deck. These imaging systems add critical situational awareness during rover positioning prior to TRIDENT drilling activities.

The primary goal of TRIDENT is to deliver subsurface regolith, including volatile-rich regolith, if present, to the surface for analysis by NIRVSS and MSOLO. In addition, TRIDENT is designed to measure subsurface temperature using one of the two drill-integrated temperature sensors. These measurements will inform the heat flow properties of the subsurface and are valuable for refining models of ice distribution across the south pole region and elucidating lunar history and processes. TRIDENT drill telemetry, including torque, power, and penetration rate, as well as camera images of the cuttings cone, can be used to constrain the geotechnical properties of the regolith.

The following sections detail the development of TRIDENT, its operation, and additional scientific information that the drill can provide to supplement NSS, MSOLO, NIRVSS, and the IMU on board the mission.

2. Trident Drill Technology Maturation

Over the past three decades, the Honeybee Robotics drilling program has targeted the use of drills and sample acquisition devices on missions to all planetary bodies that future missions are expected to explore (Y. Bar-Cohen & K. Zacny 2009, 2020). It is important to note that each planetary environment presents different physical challenges and scientific goals that impact mission and hardware designs. Therefore, each drill design, while having some commonalities, is uniquely designed for use in a specific environment to achieve specific scientific goals and objectives. Furthermore, each planetary environment varies significantly depending on the target body and the specific landing site, including temperature ranges, atmospheric pressures, and radiation levels. At Honeybee, the decades-long drilling development described below has led to TRIDENT.

TRIDENT technology for 1 m regolith drilling has been in development at Honeybee Robotics for over 20 yr under various NASA-funded programs (K. Zacny et al. 2012, 2013, 2015, 2016; G. Paulsen et al. 2015, 2016, 2018). The timeline and details of the major programs to develop and mature lunar-focused drilling systems are shown in Figure 4. It should be noted that the long timeline in the development of 1 m drilling technology was driven by the funding profile rather than engineering or technical constraints. That is, each drill iteration and step of technical progress was possible once a new source of funding became available.

TRIDENT was specifically designed to work in conjunction with the payload and science investigations on both the PRIME-1 and VIPER missions. Each mission has common payload elements and similar environmental locations, enabling identical designs for each mission. TRIDENT is an instrument that utilizes rotary, percussive, and rotary–percussive operations due to the experience developing the Construction and Resource Utilization Explorer (CRUX) drill. In the development of CRUX, several tests were conducted on materials of various compressive strengths. These tests demonstrated that an extremely high weight on bit (WOB) would be required to penetrate harder material unless percussion was included. This is a reason why, for concrete drilling or blast hole drilling, various types of hammer drills are being employed on Earth. Further, when used in the field in the Arctic, rotary drills took days to drill 1 m, whereas rotary–percussive systems took less than 1 hr (Y. Bar-Cohen & Zacny K. 2009; J. Atkinson & K. Zacny 2018). These tests concluded that planetary drills should include the ability for rotary and percussive drill modes, even though it adds mechanical complexity and power to actuate percussion. The reason for splitting rotation from percussion and enabling these two modes to be run separately is to save power and energy. There are applications when rotary drilling would suffice, and in turn, power and energy could be saved if percussion is not being triggered at the same time.

The Icebreaker drill represented a significant step in drilling technology development. The experience of Icebreaker identified several required redesigns of the CRUX hardware for future planetary usage. These innovations included redesigning the hammer mechanism to increase its efficiency, a design that enabled vacuum operation, and an improved thermal dissipation path to ensure the collection of volatiles. The new Icebreaker hardware included a vacuum-rated cam-spring hammering mechanism, a cable–pulley *Z*-stage (vertical) deployment system, a bite-sampling approach for sample delivery with an associated rotary brushing system, and drill-bit-integrated temperature sensors. The final system successfully integrated these improvements and was thoroughly tested in different environmental conditions, including temperature, pressure, and material hardness. Many of these improvements were included in the TRIDENT design.

Both CRUX and the Mars Curiosity drill use a ball screw to advance the drill auger into formation (R. C. Anderson et al. 2012). While there are similarities between Martian and lunar environments, the lunar regolith is more abrasive due to the lack of atmospheric weathering. This abrasiveness can result in an increased likelihood of potential failure of the ball screw mechanism if even a little dust enters the screw. To survive the 100 day mission lifetime and the expectations of having to drill dozens of 1 m holes during the VIPER surface mission, the decision was made to look for alternative architectures. Honeybee developed a capstan winch consisting of pulleys and a rolling carriage constrained to linear rails. This design enabled the drill head to "float" during percussive operation, allowing the percussive head to move freely with minimal support and become more resistant to abrasive lunar particulates. This is analogous to construction workers supporting jackhammers from tilting to the side and not pushing down on them or otherwise constraining them from bouncing up and down.

TRIDENT was designed to operate utilizing bite drilling through lessons learned in the CRUX development. In testing for that development, energy increased with depth due to the increased friction between the cuttings, drill stem, and borehole, as the volume of cuttings that needed to be moved along the entire length of the auger to the surface increased with depth. To reduce energy usage, operations included a

Drill name	CRUX	Icebreaker	LITA	RP	TRIDENT
	2004-2007	2008-2011	2011-2013	2014-2018	2019-2025
					
Technology readiness level	3 Function	4 Form-Function	5 Form-Fit Function	6 Form-Fit Function	9 Form-Fit Function
Technology focus	Rotary percussive drilling	Cable-Pulley, Bite Sampling, Hammer mechanism	Drill and avionics mass reduction	Vacuum and thermal design	Flight development
Lab tests	Mars chamber	Mars chamber	Mars chamber	Lunar chamber	Lunar chamber
Field tests	Arctic	Arctic, Antarctica	Atacama, Arctic, Greenland	Atacama, JSC Lunar Yard	
Rover tests			CMU Zoe	JSC RP, ARC KREX2	
Environmental tests				Vibe	Vibe, TVAC, EMI/EMC

Figure 4. 1 m Class Drill Maturation History.

bite-drilling approach analogous to peck drilling in machine-shop terminology to minimize power and energy. After each 10 cm penetration, the drill would be retracted from the hole to clear the cuttings and replaced into the borehole to achieve 10 cm further in depth. To increase efficiency in capturing cuttings, the auger's "bite" section was redesigned to include deeper flutes. A passive brush, forming a worm gear configuration with the auger, was included in the lower section of the drill to scrape off the cuttings as the drill string is retracted from the borehole. This design also improved the spatial resolution of the subsurface to 10 cm depths, enhancing the scientific value of measurements by NSS, MSOLO, and NIRVSS.

The Life In The Atacama (LITA) drill incorporated improvements in electronics and operational efficiency while reducing the mass and volume of the drill hardware. The Icebreaker drill had a mass of over 50 kg, while the LITA drill had a mass of 15 kg. LITA was also the first Honeybee drill incorporated onto a rover to test drilling on a lighter, potentially less stable platform. LITA was integrated into the Carnegie Mellon University (CMU) Zoe rover and deployed several times in the Atacama Desert. The LITA design was also tested on Devon Island in the Arctic, Greenland, and Mars-relevant chambers to characterize drilling operations in different environments.

The Resource Prospector (RP) drill was specifically designed and tested for lunar operations, including operating at extremely low temperatures with vacuum-rated lubrication. RP's design evolved the LITA drilling mechanism to withstand dust abrasion while extending the life of critical subsystems (e.g., brush, cables). The RP drill was demonstrated in the VF13 lunar chamber at NASA Glenn Research Center (J. Kleinhenz et al. 2015). The RP drill was also integrated into the RP rover prototype at NASA JSC. This drill represents the final technology development effort, achieving a technology readiness level of 6, and served as the primary design of the TRIDENT drill.

Designing a drilling system is complicated, with many free parameters present in the drill string design, including flute depth, helix angle, and rake angle, to name a few. During the 20 yr of technology development, each drilling test added to the knowledge of how to build a planetary drilling system. TRIDENT builds on the experience of each funded program, including many other programs not listed here, in developing, testing, and deploying these drilling systems. TRIDENT's design incorporates designs to meet the mission requirements for PRIME-1 and VIPER, including mass limitations, power profiles, and remote operational scenarios. The physical parameters of the regolith at the landing sites have not yet been measured, so TRIDENT was developed to drill into material with a wide range of parameters, including compressive strength and volatile content.

3. Description of the Trident Drill

TRIDENT consists of six subsystems, as shown in Figures 5 and 6: (1) a rotary–percussive drill head for providing percussion and rotation to the drill string; (2) a linear deployment stage for deploying and preloading the drill to the ground; (3) a linear feed stage for advancing the drill string up to 1 m below the subsurface; (4) a drill string with a drill bit, two temperature sensors, and a heater for drilling, sample capture, and thermal measurements; (5) a brushing station for brushing off and depositing material onto the surface; and (6) avionics with embedded software for powering and operating the drill (Y. Bar-Cohen & K. Zacny 2020; K. Zacny et al. 2022).

The drill parameters can be found in Table 1. The drill (including launch locks) has a mass of 19.5 kg. The avionics box comprises four motor drivers, a thermal card, a power distribution unit, and a command and data handling board. The drill bit, which contains a percussive-grade carbide tip, has a diameter of 25.4 mm (1 inch). The nominal rotary speed of the auger is 90–100 rpm, but it can be increased to 120 rpm if needed. All four TRIDENT actuators utilize brushless DC (BLDC) motors with various planetary, spur, and bevel gearing combinations to achieve the appropriate output speed and torque. The drill head consists of two actuators within an enclosed housing, one for driving the rotation of the auger and one for controlling the percussive hammering mechanism. The percussive system can be actuated as needed during drilling to penetrate harder formations. It uses a cam-spring percussive mechanism to provide 2 J blow^{-1} at up to 972 blows per minute. Percussive frequency can be varied depending on mission needs; for example, a single hammer blow can be delivered to perform a seismic survey in conjunction with a spacecraft IMU. Percussion is normally initiated when drilling into hard material to reduce auger torque and prevent binding in the hole, as well as to empty the auger of cuttings during sample delivery on the lunar surface. During drilling, the percussive system is typically actuated autonomously when feedback from other systems indicates that the drill is making insufficient progress into the subsurface.

Two nested linear stages are used to enable drilling, as shown in Figure 6. The deploy and feed stages consist of carriage wheels that roll on linear rails. The deploy stage controls the position of a footpad, which is first preloaded against the surface to provide stability during drilling. The feed stage controls the depth of the drill string and has additional length to allow the drill string to be fully extracted from the borehole, such that any sample near the tip of the drill string can be brushed away using the passive sampling brush. Each linear stage is controlled using a steel wire rope capstan mechanism driven by a BLDC actuator. Redundant microswitches on each linear stage assist in returning the linear stages to their home positions.

Additional features of TRIDENT include multiple flex harnesses used to transmit power and data across the full range of motion of the deploy and feed stages and a set of launch locks for constraining the motion of these stages against launch vibration. The drill head also contains a rotary slip ring for transmitting power and data to the heater and dual platinum resistance thermometers (PRTs) within the drill string. Kapton film heaters are used throughout the system to warm avionics and actuators to flight operational temperatures.

The TRIDENT avionics system provides power and control for the drill actuators, temperature sensors, and heaters. It also includes onboard software, which provides both low-level motor control and high-level logic to control TRIDENT operations. Honeybee Robotics also developed dedicated ground software to enable TRIDENT operators to remotely control the drill in near real time from ground stations at NASA Kennedy Space Center on PRIME-1 and NASA Ames Research Center for VIPER.

As mentioned earlier, TRIDENT uses a bite-sampling approach to drilling and sample delivery as follows. After drilling ∼10 cm into the subsurface, the drill is retracted, and the cuttings are deposited onto the surface using a rotary brush guided by a chute. Once on the surface, the cuttings are analyzed by the NIRVSS and MSOLO instruments (Figure 7). Upon completion of the analysis, the drill is lowered back into the hole to cut another 10 cm bite (i.e., from 10 to 20 cm depth) and present new subsurface material for analysis. A bite size of 10 cm is nominal but can be shorter, if requested.

The bite-sampling approach has several advantages related to science and drilling (K. Zacny et al. 2013). From a scientific standpoint, since cuttings are removed in bites, a 10 cm stratigraphy is retained. In addition, when the drill is lowered back into the empty hole, assuming the cuttings have enough cohesive strength not to fall into the borehole (G. Heiken et al. 1991), the initial drilling torque can be attributed to material strength alone. In a borehole filled with cuttings, the drilling torque would be a product of drilling and chip removal using the auger. In some instances, the contribution of the chips' transport torque could be greater than the torque attributed to drilling alone. For this reason, drilling in a series of bites allows for a lower average drilling torque, as cuttings do not need to be transported over a large vertical distance to the surface. This is the most significant advantage from the augering standpoint. The bite-sampling approach also offers some thermal advantages—namely, the drill bit has time to

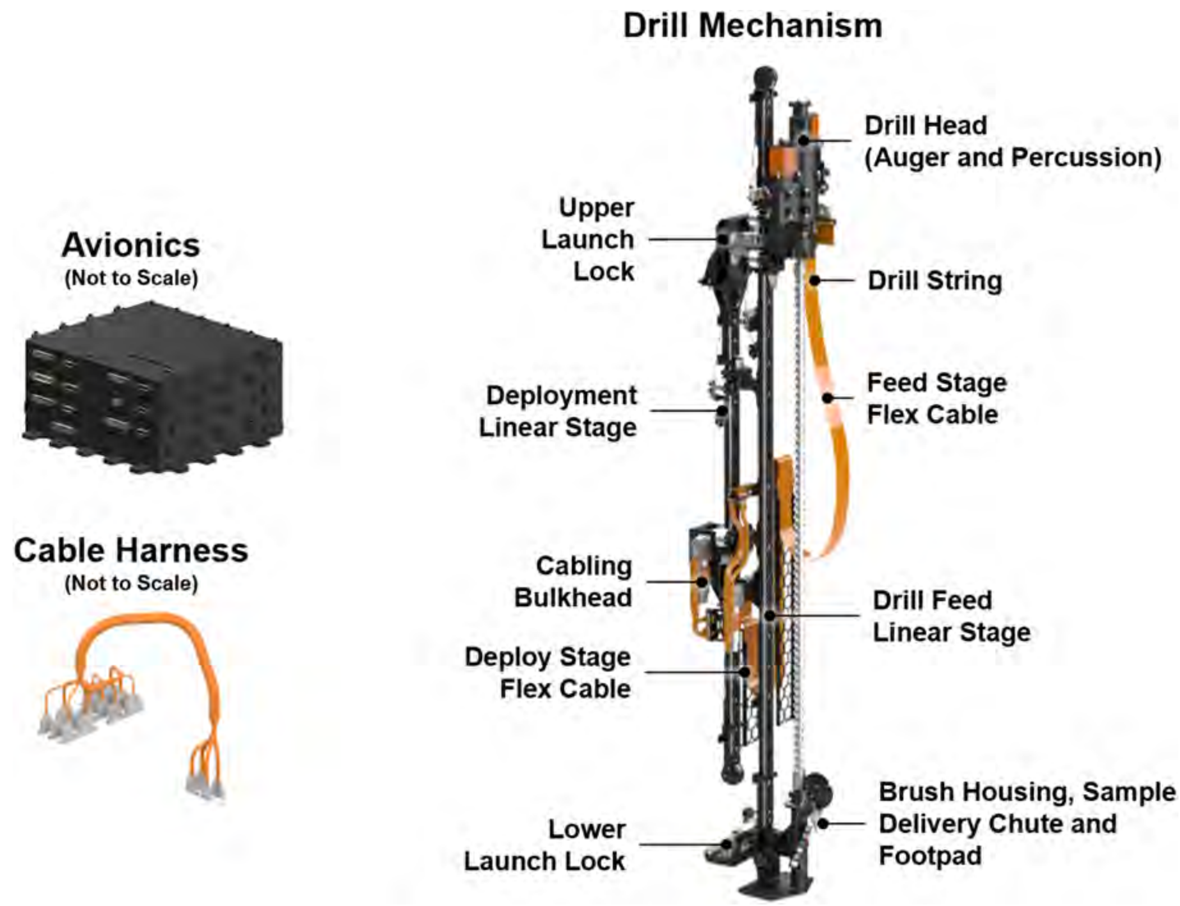

Figure 5. The TRIDENT drill subsystems. The drill is ∼1.75 m tall.

cool off once on the surface, and this also helps in retention of volatiles.

As shown in Figure 7, the auger drill string has been divided into two sections to support the bite-sampling approach. The lower section, the sampling auger, is designed with deeper flutes to promote sample retention. As such, once the material is "jammed" inside, it is less likely to fall out. The more extended upper section is designed with shallower flutes for efficient material conveyance out of the hole. As such, cuttings will most likely be augered out or fall off once on the surface. Combining the two auger geometries means the system is designed for efficient sampling but inefficient conveyance. If the drill is used in the non-nominal case of drilling to a full 1 m depth in a single run, it will increase the drilling torque and power with an increased likelihood due to excessive cutting buildup.

4. Operation of Trident

TRIDENT consists of the drill hardware, avionics with control software, and ground software. For lunar operations, the system was designed for real-time operations, where human operators monitor drill telemetry and make operations modifications in near real time. This enables operators to identify potential faults and adjust drilling operations in real time, simplifying avionics development while avoiding drill slippage, clogging, or other unanticipated operations.

Onboard software consists of low-level motor control software used to commutate BLDC motors and higher-level operations that command the position and velocity of each actuator to perform various functions. These operations include releasing launch locks, performing actuator calibration, deploying the stabilizing footpad, drilling, retracting the drill string to deposit cuttings, and stowing the drill in its home position. Each function has software logic to string together lower-level actuator commands using a set of user-defined parameters. The ground data system is called Poseidon and is a graphical user interface that enables users to interface with the drill. Poseidon allows operators to adjust the command parameters of each operation, send the command, and view an acknowledgment that the avionics received the command. Poseidon reports telemetry and drill status during operations through status indicators, telemetry fields, plots, and event records. Multiple TRIDENT operators monitor this telemetry to assess the health and safety of the drill during operations. Telemetry is saved for later analysis for anomaly investigation and to generate geotechnical analysis of subsurface conditions.

The TRIDENT operations team consists of three roles: Payload Uplink Lead (PUL), Payload Downlink Lead (PDL), and TRIDENT Science. Role descriptions for VIPER are provided in Table 2. The operator configuration and nominal communication channels are provided in Figure 8.

Since the PRIME-1 mission contained fewer instruments and operators than VIPER, all TRIDENT operators were able to be colocated with MSOLO in the Joint Information Center. TRIDENT operator roles were roughly the same as those

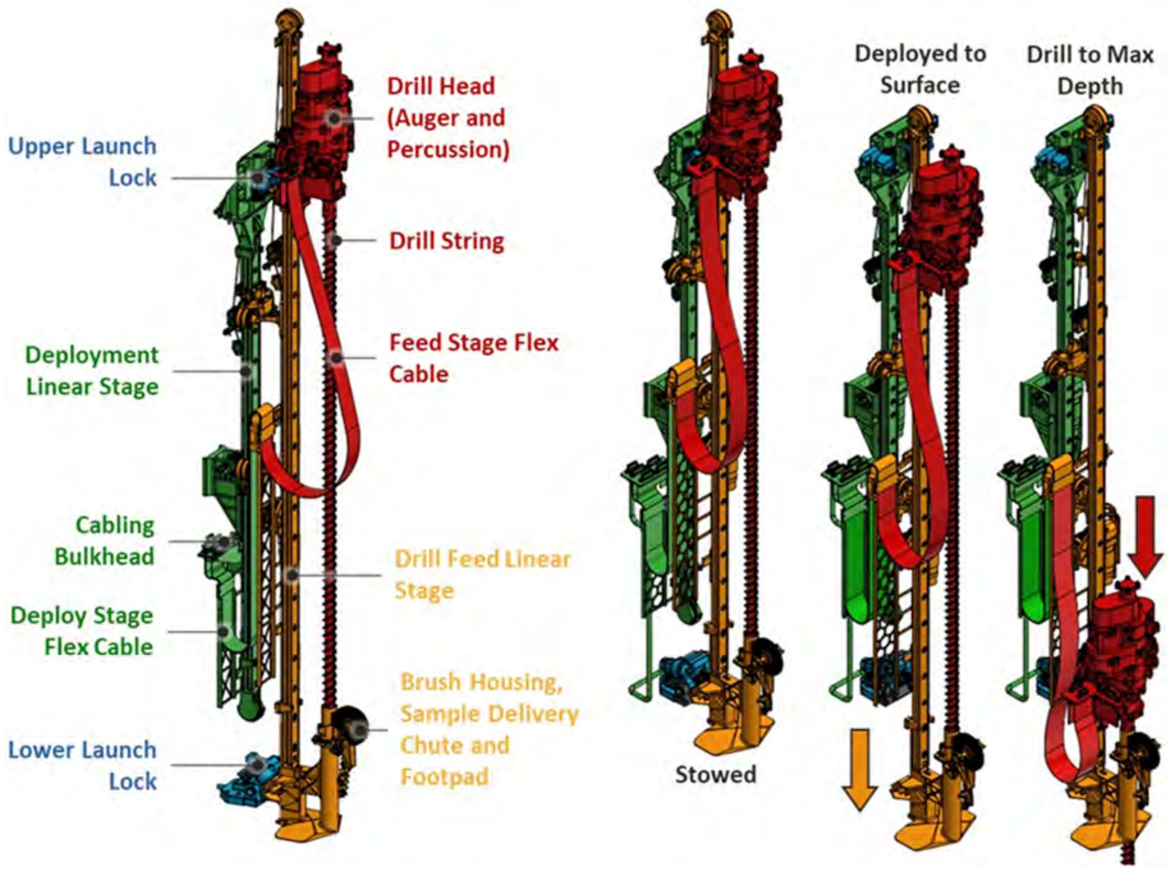

Figure 6. The TRIDENT deployment linear stage and drill feed linear stage are used to deploy the footpad to the surface and feed the drill bit and drill head into the ground during drilling. Actuator control and power transmission are accomplished using flex cables.

Table 1
Characteristics of the TRIDENT Drill

TRIDENT Parameter	Characteristic
Overall mass	26.5 kg
Drill hardware mass	19.5 kg
Avionics mass	7 kg
Drill diameter	25.4 mm (1 Inch)
Drill length	1 m
Percussive energy	2 J $blow^{-1}$ @ 972 blows per minute
Rotary power	50 W (nominal)

described in Table 2, but because drill sites could not be selected given the lander architecture on PRIME-1, this was not part of the TRIDENT Science responsibilities. Instead, for this mission, due to its more relaxed pace of operations and longer science holds, the TRIDENT Science role was planned to have an added emphasis on coordination with MSOLO Science to help provide additional drilling context using near-real-time evaluation tools. For example, drilling behavior analyzed by TRIDENT Science can influence the interpretation of MSOLO measurements and possibly help guide MSOLO instrument tuning for future drill bites.

TRIDENT operators utilize a procedure development program called PRIDE to organize activities and sequence various operations. PRIDE allows TRIDENT operations to be synchronized with the other instruments (MSOLO and NIRVSS) for real-time adjustment of their operational parameters of observing cuttings during a drilling activity.

TRIDENT operators utilize voice communications to coordinate with each other and the broader VIPER and PRIME-1 teams. Operational simulations have been, and continue to be, performed to train console operators in all aspects of TRIDENT operations. Figures 9 and 10 show the integration of the TRIDENT hardware on the IM-2 lander and VIPER.

5. Preflight Testing of Trident Drill

Flight units (FUs) of TRIDENT drills for the PRIME-1 and VIPER missions underwent environmental testing to confirm meeting mission requirements. These tests included thermal vacuum tests, vibration (sine and random), shock, and electromagnetic interference/electromagnetic compatibility (EMI/EMC). Anomalies detected during testing were addressed and further tested to ensure they met mission requirements (P. Chu et al. 2024). To limit wear on the flight drill string, identical strings were used during testing and replaced after testing. Assembly was performed in a 10K (ISO7) clean room, and flight drill strings were never used to perform drilling tests in regolith simulants. These drills are shown in Figure 11.

Further testing to determine drill behavior and mechanism life was done with a TRIDENT dedicated engineering unit (EU). Using the EU in a dirty drilling test campaign in rocks and lunar regolith simulants allowed the FU to remain pristine and allowed for the testing of more extreme samples to stress the system beyond nominal. Over the course of this testing, the TRIDENT EU drilled nearly 30 m in ~1 m intervals, with a

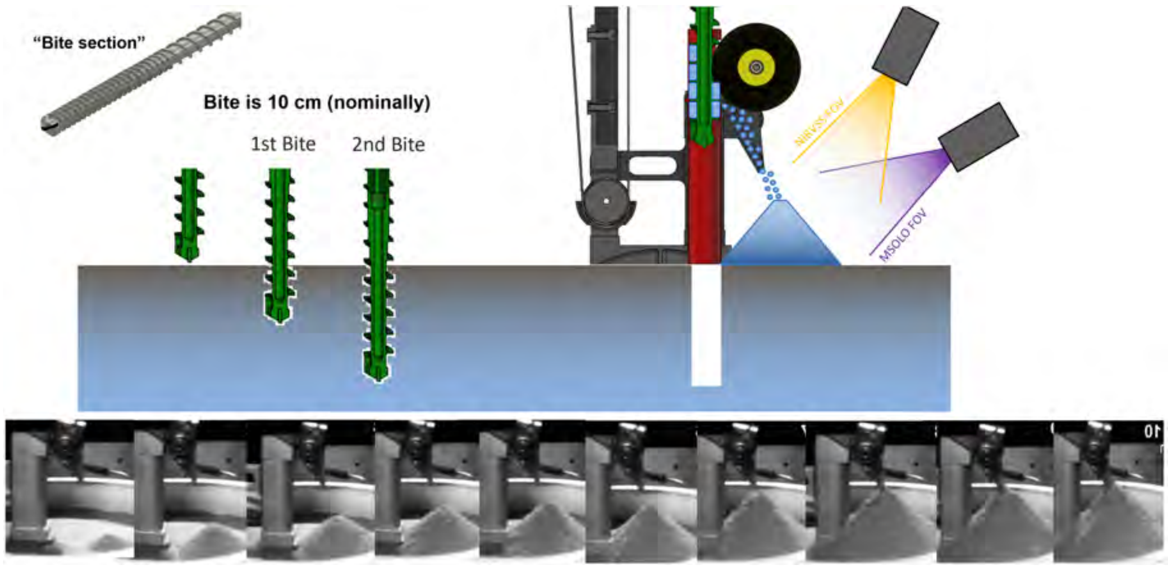

Figure 7. TRIDENT uses a bite-sampling approach. The bottom images show actual cuttings cones formed by delivering 8 cm deep bites to the surface from an 80 cm deep hole. The drill string (upper left) shows the "bite" flute design to increase sample retention in each 10 cm bite.

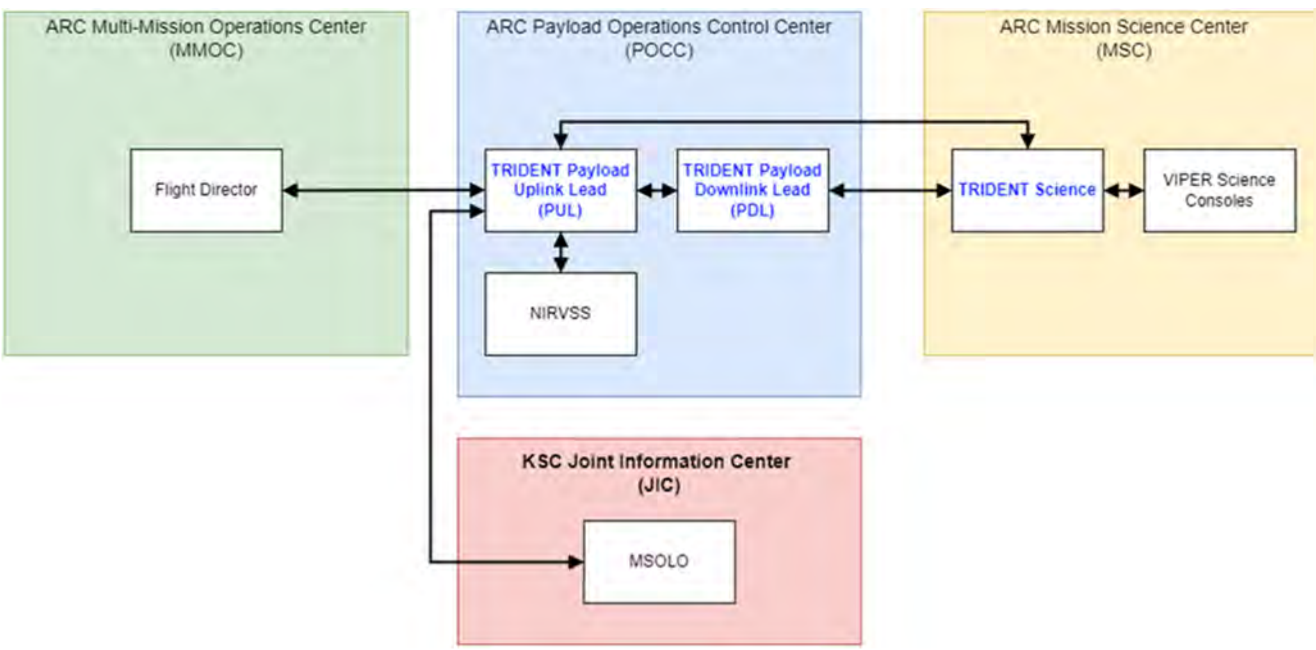

Figure 8. Typical locations and channels of communication for TRIDENT operations on VIPER.

Table 2
TRIDENT Operator Roles and Their Associated Responsibilities

Role	Location	Responsibility
PUL	Payload Operations Control Center	Overall lead for TRIDENT operations, driving execution of procedures Responsible for sending all commands to TRIDENT Single point of contact for the flight director and the rest of the mission operations team
PDL	Payload Operations Control Center	Responsible for monitoring telemetry received from TRIDENT Provides awareness of the instrument health and status to the PUL
TRIDENT Science	Mission Science Center	Represents TRIDENT in discussions in the Mission Science Center, including drill site selection Provides recommendations to the PUL regarding final drill site approval Advises the TRIDENT ops team when drilling conditions warrant deviation from the standard procedure

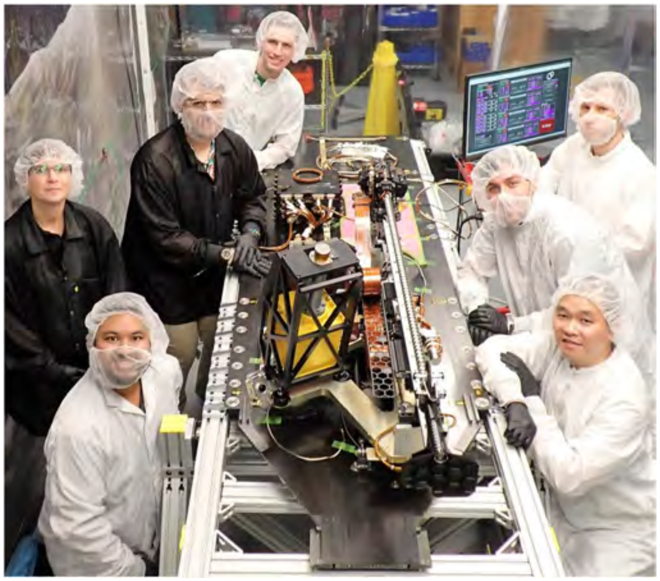

Figure 9. TRIDENT integration team following the installation of the TRIDENT FU and avionics onto an IM-2 lander panel at Intuitive Machines in Houston. Courtesy NASA Bill Stafford.

Figure 10. Moments before integrating the VIPER TRIDENT FU into the chassis of VIPER at Johnson Space Center in Houston. Courtesy NASA Bill Stafford.

total of 337 bites under various conditions of temperature, pressure, and different simulated material.

The majority of TRIDENT EU tests were performed in lunar regolith simulants designed to test operational requirements, including optimizing cuttings conveyance, demonstrating mechanism dust tolerance, and capturing drilling behavior in icy soil. For icy soils specifically, testing was designed to understand the thermal characteristics of the drill bit and the ability to deliver volatile-rich material to the surface. Two lunar regolith simulants were used: NU-LHT-2M (X. Zeng et al. 2010) and Lunar South Pole High-Fidelity Moon Dust Simulant (LSP-2) from the University of Central Florida's Exolith lab. These simulants were prepared at ambient conditions (20 °C, 760 Torr) and conditioned to simulate the lunar environment (<−100 °C, at <1e-4 Torr). Ice concentration included samples doped with up to 8.5 wt% H_2O. Care was made to limit the amount of sublimated water ice from the system by systematically lowering the temperature and pressure to stay under sublimation conditions while the environmental parameters were achieved. On PRIME-1 and VIPER, qualitative volatile measurements were not baselined; thus, complex methods for making lunar ice were not utilized, although in future developments, they will be considered depending on mission objectives (D. Ricardo et al. 2023; D. K. Johnson et al. 2024; K. Šļumba et al. 2024). The environmental test chamber is on site in the Honeybee Robotics geotechnical laboratory, as shown in Figure 12.

In all tests in the lunar regolith simulant, cameras were mounted to approximate the viewing angle of the NIRVSS AIM camera (Figure 13). This was done to calibrate the cameras to cone geometry so it could be related to drilling depth. This generally sets the expectations for drilling visibility during flight operations.

Aside from testing in a lunar regolith simulant, another subset of drilling tests was performed in commercial rocks. These tests were intended to satisfy two primary objectives: verify drilling performance in the most challenging expected conditions and develop a baseline relationship between unconfined compressive strength (UCS) and specific drilling energy (SDE). The rocks used in these tests include Texas Cordova Cream limestone, Indiana limestone, Berea sandstone, and Saddleback basalt, which were intentionally selected to cover a wide range of compressive strengths (roughly 20–120 MPa) for development of the SDE baseline. To cover the lower range of UCS, commercial Aircrete was used (4 MPa, 420 kg m^{-3}). These tests were all performed in ambient conditions, except for a 1 m hole drilled in the Texas Cordova Cream limestone, which was conducted in vacuum (<1e-4 Torr) with percussion continuously applied to observe heat dissipation in the TRIDENT drill head. The results of these tests are discussed in the next section.

A standard set of drilling parameters was developed from TRIDENT EU testing. While these parameters are expected to perform well in most drilling scenarios, Honeybee built the flexibility to change many parameters after monitoring drilling success on the lunar surface. This operational flexibility enables a quick response to unexpected conditions and behaviors occurring during lunar surface operations. Prelaunch baseline parameters include a 100 rpm auger/spindle rotational speed during drilling and 15 rpm during retraction. For drilling into fresh material, the feed speed set point is baselined at 1.25 mm s^{-1}, which provides precise control of the WOB. To minimize total drilling time, a faster feed rate of 2 mm s^{-1} is used during retraction and in most other operations that do not require precise WOB control. WOB is typically limited to 100 N, and the percussion rate is set to 729 bpm to maintain 8.1 blows per revolution (assuming a 100 rpm auger rotational speed). Table 3 lists the parameters of the initial operation and values that can be used to respond to unknown conditions.

TRIDENT's EU was tested for over 30 hr in a wide variety of environments and vastly different rock types. These testing results demonstrated no measurable effects of dust ingress on

Figure 11. TRIDENT FUs for VIPER (left) and PRIME-1 (right) staged in the Honeybee Robotics clean room prior to delivery.

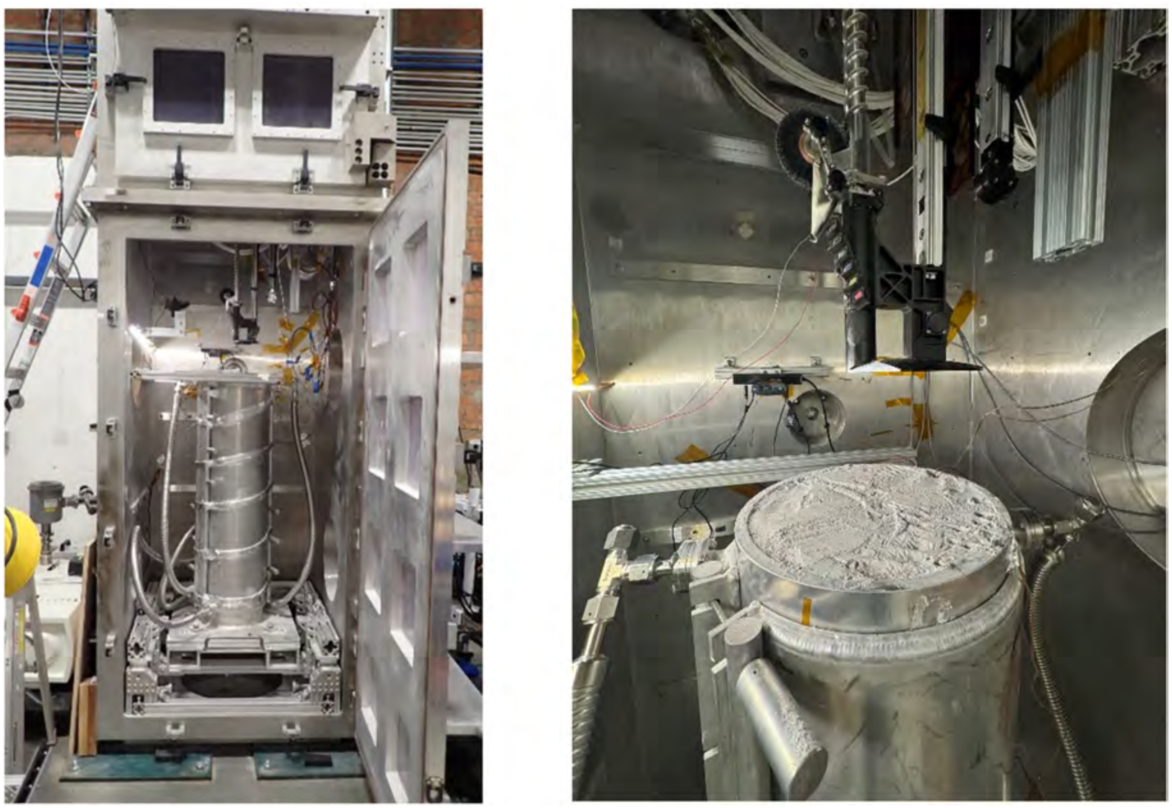

Figure 12. Environmental test chamber used to simulate a lunar environment for TRIDENT EU testing. The bin is approximately 30 cm in diameter.

actuator no-load currents. This implies that the system has a high dust tolerance and will be robust to the expected operational environment.

As mentioned previously, during the PRIME-1 mission, there was enough power to test the operational functioning of the drill, even though the lander was on its side. All the actuators on the drill performed as expected. The drill went through the multiple stages that would nominally be required for drilling on the lunar surface through the full range of motion. The auger rotated and percussion was commanded and worked as expected, given the position of the lander and the excess dust that landed on the systems. The internal thermal sensors of the core heater both monitored and measured temperature change due to the heaters. Under the off-nominal landing conditions, the drill performed exactly as it did in its preflight testing.

Figure 13. Camera view during TRIDENT EU testing simulates the NIRVSS AIM camera view on VIPER.

Table 3
TRIDENT Operational Parameters for Initial Drilling and Potential Values

Operation	Nominal Operational Value	Potential Operational Values
Drilling speed	100 rpm	10–120 rpm
Incremental depth	10 cm	1–10 cm
Retraction speed	15 rpm	10–120 rpm
Feed speed	1.25 mm s^{-1}	0–4 mm s^{-1}
Percussion rate	729 bpm	0–1000 bpm
WOB	100 N	0–500 N

Note. TRIDENT was developed to respond to unforeseen drilling conditions on the lunar surface.

6. Science Data from Trident

6.1. Lunar Subsurface Environments

The VIPER data will address the VIPER mission science objectives and test relevant hypotheses regarding polar volatile sources, sinks, retention, and distribution. The VIPER traverse will explore different regions consisting of areas defined by their ice stability depth. Ice stability depths are modeled with orbital data combined with known ice thermodynamic properties to determine the most likely depths of water-ice stability over geologic timescales (M. A. Siegler et al. 2016; J. Coyan et al. 2025, this issue). These maps provide a spatial proxy for ice stability regions (ISRs), a convolution of ice stability depth and total overburden. Four ISR types have been identified and will be explored during the mission. ISR type “surficial” describes regions where surface temperatures are sufficient for ice to be stable at the surface. ISR type “shallow” describes regions where ice could be stable at depths from the surface to 20 cm deep. ISR type “deep” describes regions where ice could be stable at depths between 20 and 85 cm deep. Finally, ISR type “dry” describes regions where ice should not be stable anywhere from the surface to below 85 cm depth. To meet mission measurement requirements, areas of $\sim$3800 m^2 with a dominant (>66% by area) ISR type are of high scientific interest in the design of the VIPER traverse.

Within each science station, defined as having at least 66% of its area be a single ISR type, TRIDENT will nominally be deployed three times over the 100 Earth-day mission life for drilling. The third drill location within each ISR will be targeted tactically with real-time science team guidance. TRIDENT will provide critical in situ investigations on how regolith geotechnical properties and the lunar subsurface thermal environment vary due to ISR type and local environmental characteristics, including volatile content measured by NIRVSS, MSOLO, and NSS (D. S. S. Lim et al. 2024). These investigations will enable the team to validate and inform geostatistical models of water-ice prospectivity (J. Coyan et al. 2025, this issue) and provide significant new constraints on the horizontal and vertical distribution and heterogeneity of lunar polar volatiles.

In addition to providing samples for in situ analysis by NIRVSS and MSOLO, TRIDENT can provide information about the lunar geotechnical and thermal subsurface environment. Further, geotechnical properties as constrained by

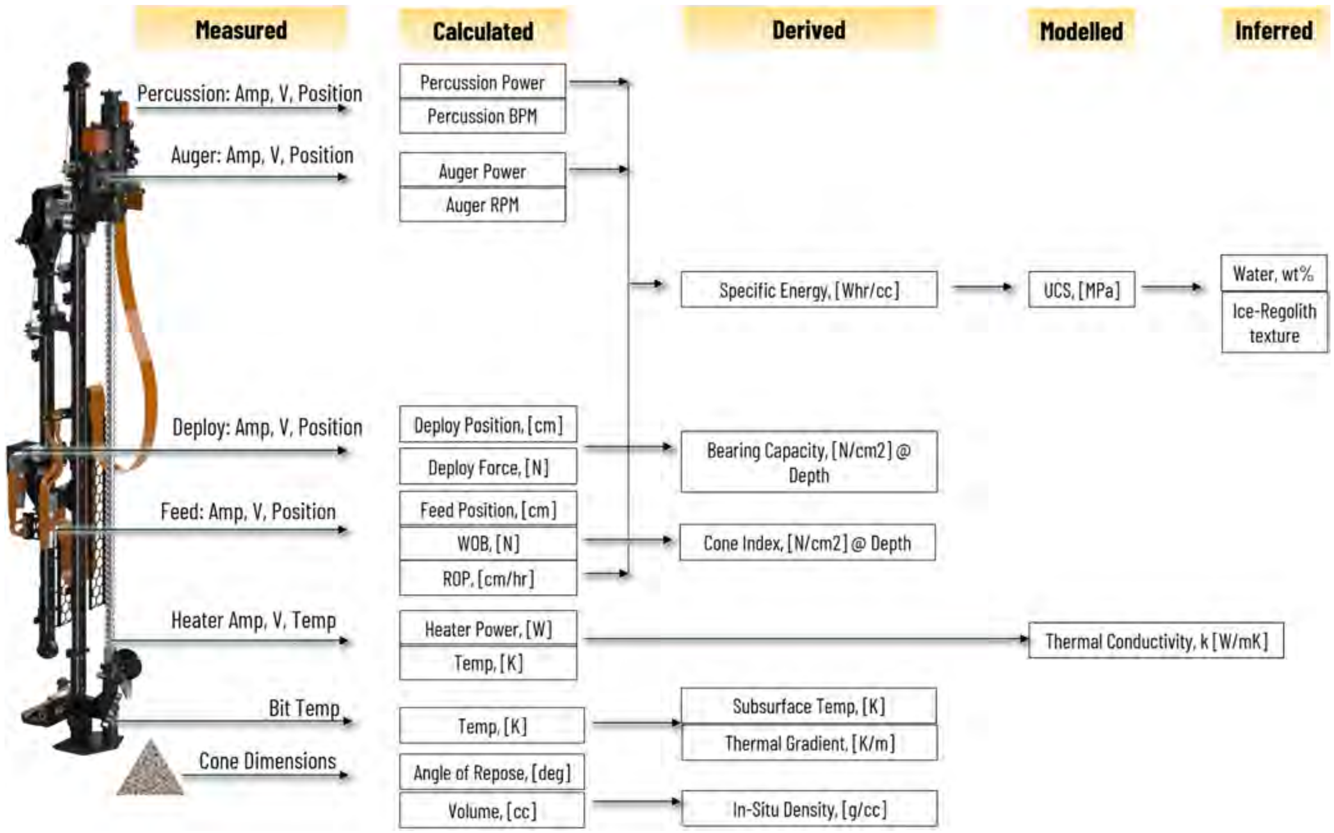

Figure 14. Drilling data from TRIDENT (K. Zacny & P. Chu 2024).

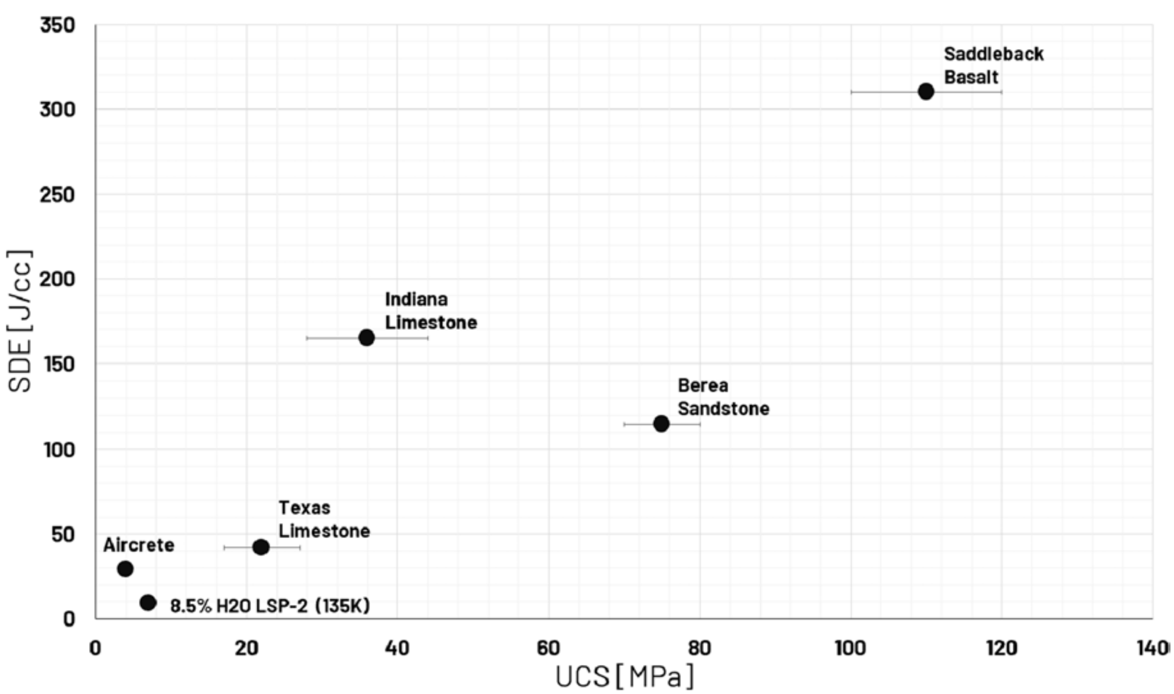

Figure 15. SDE compared to the measured UCS of rocks during TRIDENT testing. This baseline can generate an empirical model that takes measured operational parameters and determines a range of in situ material hardness.

TRIDENT can be extrapolated laterally (between boreholes) using data derived from rover wheel tracks and the suspension system (E. Rezich et al. 2025, this issue). Figure 14 shows the flow of data collected during a drilling operation and how it is used to understand the physical parameters present in the sampled material (K. Zacny et al. 2006; K. Zacny & P. Chu 2024). The flow from measured data to scientific utility is only as good as the inputs to the models. During testing, measured and derived parameters were calibrated to known material properties so that they could be used in modeling efforts.

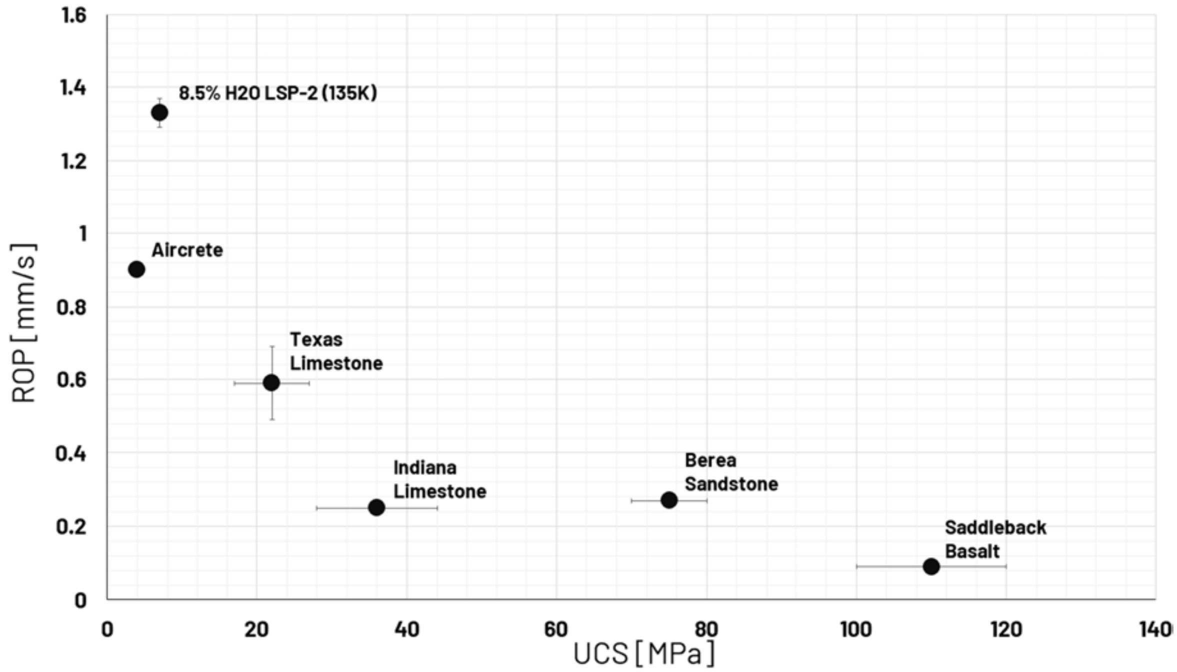

Figure 16. ROP when drilling rocks of varying UCS with TRIDENT baseline parameters.

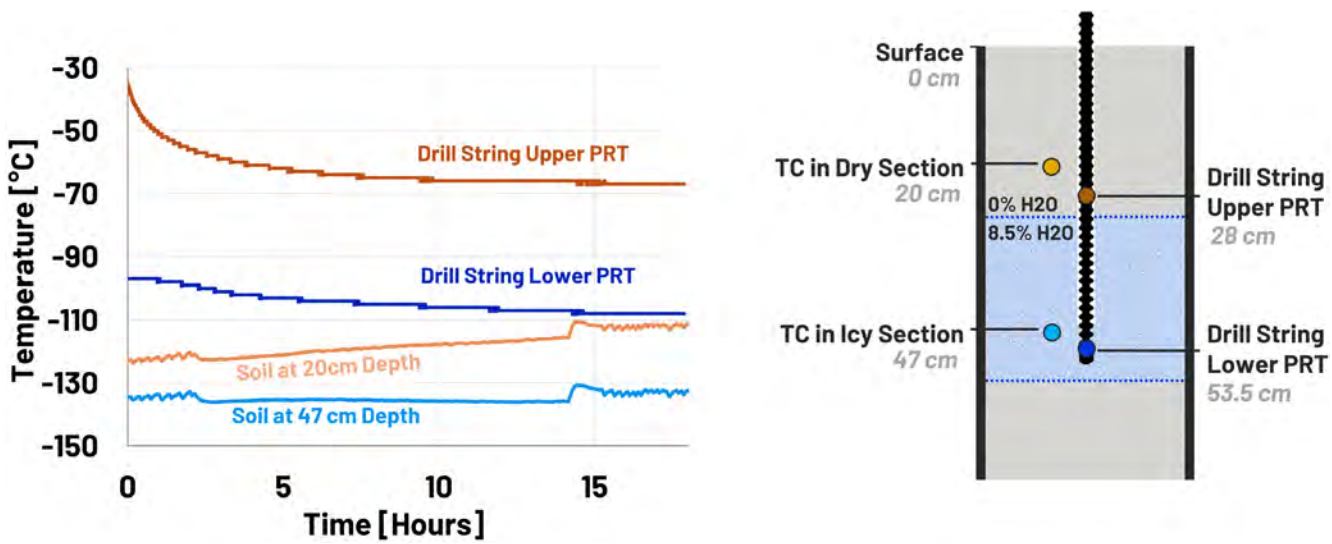

Figure 17. Example drill bit temperature measurement at 50 cm depth performed by the TRIDENT EU in a water-doped lunar regolith simulant (8.5 wt% H_2O LSP-2) in a vacuum. Nearby soil temperatures are provided for reference.

Derived measurements of specific energy for drilling can be determined from the specific energy of percussion and calculated from the product of the rate of percussion, drilling time, and energy per blow per unit volume. The cone index can be derived from the WOB and penetration rate before drilling begins. The subsurface temperature and thermal gradient are measured. The development of complex models requires a more flight-like setup, allowing them to be validated with known samples (Peters et al. 2018). Finally, for icy samples, more ice/soil mixtures that are more similar to those found on the Moon need to be done. Additional modeling efforts will be conducted on an as-needed basis by performing further laboratory testing with the TRIDENT EU in a simulated lunar environment.

6.2. Data Collection and Model Development in Testing

Raw data channels, including voltage, current, and motor counts, are collected during operations. This telemetry will be used to derive parameters, such as auger torque, and analyze drilling performance. These data also allow for some characterization of the lunar subsurface, including soil properties and rock hardness (K. Zacny et al. 2006). Taking this a step further, SDE can then be derived using this telemetry through simple equations and known geometry (Y. Bar-Cohen & K. Zacny 2009; G. H. Peters et al. 2018).

During TRIDENT EU testing, data were collected in real time in an identical format to the in situ data that will be generated during lunar operations. The raw telemetry (auger speed, auger current, percussion counts, feed position)

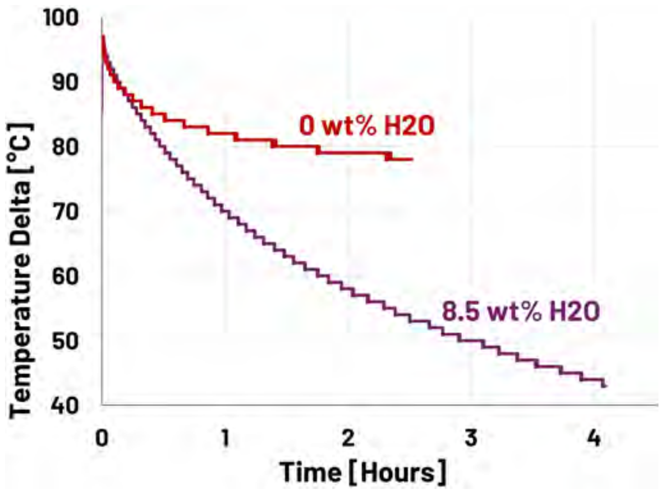

Figure 18. Difference in bit temperature and soil temperature over time. There is a notable difference in behavior between dry and icy soil, as the lunar soil is insulating and the drill stem retains much more heat in dry soil. The step pattern is due to the temperature being shown to within 1°.

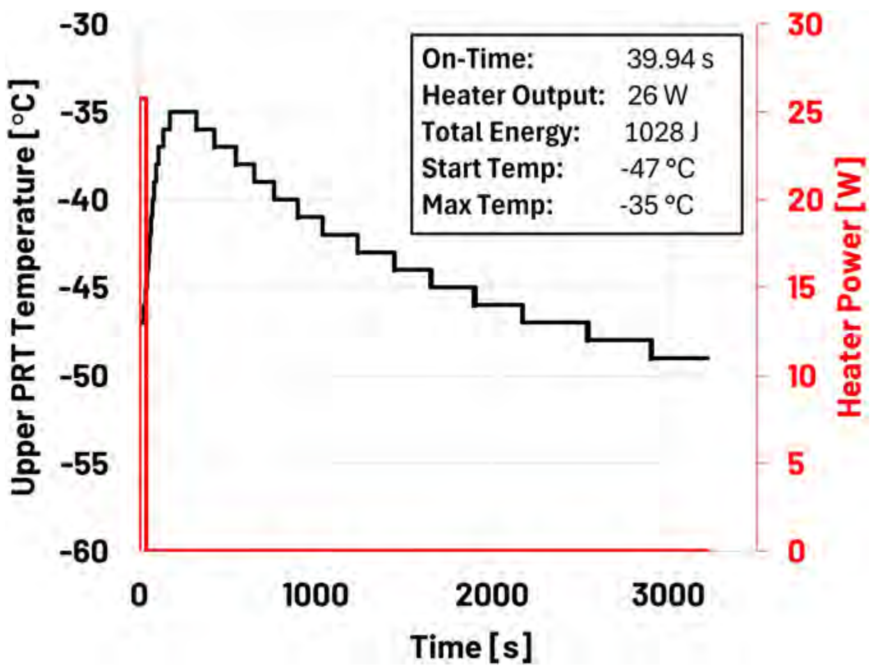

Figure 19. Example heater telemetry collected during TRIDENT EU testing in an icy lunar regolith simulant (8.5 wt% H_2O LSP-2) provides total energy and power supplied, along with temperature response from a nearby PRT. The step pattern is due to the temperature being shown to within 1°.

collected from testing in rocks of known compressive strength has been used to generate a baseline for an empirical model that relates SDE and UCS as shown in Figure 15. A second model is being developed to use raw feed position telemetry to calculate the rate of penetration (ROP), which has an inverse relationship with UCS, as shown in Figure 16.

Using these baselines, SDE and ROP computed from flight telemetry will allow for approximating the strength of subsurface (over)consolidated, icy regolith and ground ice material in situ.

Passive bit temperature curves will provide a measurement of the subsurface thermal gradient by taking temperature measurements at various depths; an example is shown in Figure 17. Testing has also shown that these measurements can provide qualitative cues to the presence of water-ice deposits in lunar regolith using observed changes in cooling rate. Baseline bit cooling data were collected during the previously described TRIDENT EU testing campaign in the LSP-2 simulant doped with 0 wt%, 4.1 wt%, and 8.5 wt% H_2O demonstrating this effect, shown in Figure 18. Taking this a step further, the onboard drill string heater, which is primarily a contingency response feature, can be used as a heat source with a known power input (Figure 19). Thus, with additional modeling and testing efforts, the TRIDENT drill string can be used as a heat flow probe to measure thermal conductivity. The only lunar heat flow measurements that have been performed include a handheld drill on Apollo 15 and 17 (M. G. Langseth et al. 1972; M. Grott et al. 2010), Chandra's Surface Thermophysical Experiment on board the Chandrayaan 3 lander (N. Mathew et al. 2025), and, most recently, Lunar Instrumentation for Subsurface Thermal Exploration

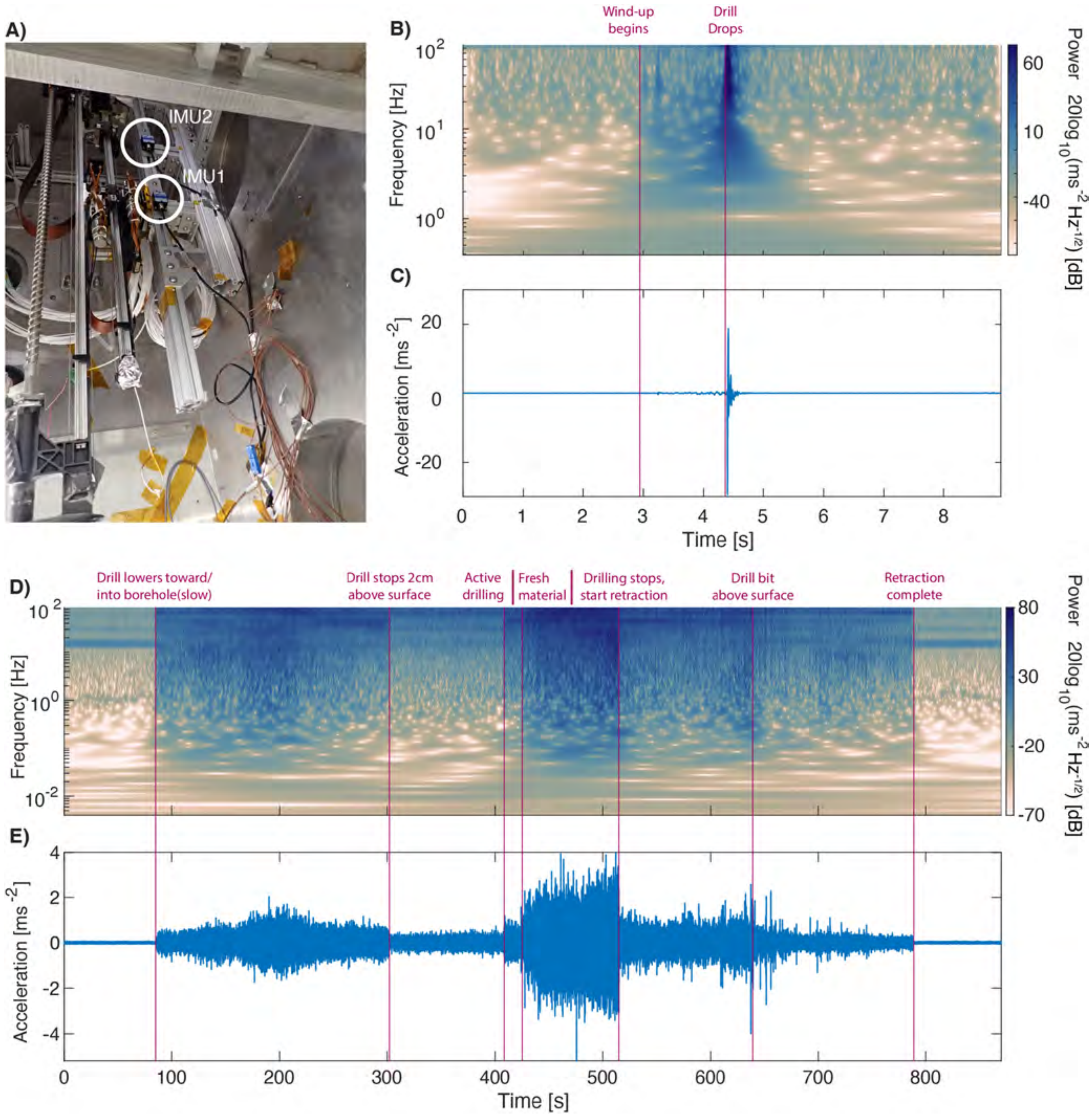

Figure 20. Example seismic recordings of TRIDENT drilling operations by a commercial IMU. (A) Two WitMotion SINDT-TTL accelerometers positioned on the drill housing ∼20 cm apart, with the $+Y$-axis in the direction of gravity. Data shown are from the vertical component of IMU1. (B) Continuous wavelet transform analysis (J. M. Lilly 2017) of a single percussion by the drill with labeling of events. (C) Accelerogram for ±4 s around the percussion window. (D) Continuous wavelet transform for IMU data acquired during bite 4 while drilling from 30 to 40 cm in the TRIDENT EU testing with labeling of events. (E) IMU1 accelerogram for drilling operations during bite 4.

with Rapidity on the Firefly Blue Ghost 1 mission to Mare Crisium (K. Zacny et al. 2013; S. Nagihara et al. 2014, 2025).

6.3. Future Development and Scientific Investigations

Other ongoing investigations of TRIDENT science capabilities include a modified footpad deployment technique to measure the modulus of subgrade reaction (k) and ultimate bearing capacity by using position data and current limiting, allowing for the development of a force-penetration curve (I. King 2024). Measures of k have been used in the Apollo era to characterize the geomechanical behavior of the lunar surface, for example, to constrain the sinkage of ALSEP experiment packages (G. Heiken et al. 1991). This has been demonstrated in the NU-LHT-2M simulant, where the footpad is deployed with two different force limits and relative displacement is obtained from position telemetry. The high-fidelity TRIDENT measures of k (and bearing capacity) can be laterally extrapolated along VIPER's traverse using wheel sinkage and data derived from the rover's mobility and actuation system (E. Rezich et al. 2025, this issue).

The TRIDENT percussion mechanism is currently being investigated as a seismic excitation source (K. Gansler et al. 2024). During the TRIDENT EU testing, two commercial-grade WitMotion SINDT-TTLs were positioned on the chassis of the TRIDENT drill assembly (Figure 20). These instruments are a three-component strong motion accelerometer and tilt sensors and a noise floor of −60 dB relative to 1 ms^{-2}.[8] In these laboratory tests, data were acquired with a sampling rate of 200 Hz on the instruments. However, on both PRIME-1 and VIPER, the included flight IMUs sample at a rate of 100 Hz, which may complicate data analysis, as signals with frequencies greater than 50 Hz may not be recorded. If this opportunistic science is found to have value, future IMUs can be selected with a higher sampling rate and minimal mission cost.

Figure 20 shows that the percussive (Figure 20(B)) and rotary and rotary–percussive modes (Figure 20(D)) of TRIDENT are detectable well above the environmental and instrument noise floor by over 62 and 76 dB, respectively. A single ∼2 J percussion of TRIDENT creates a >50 Hz impulse with an amplitude of 60–80 dB on the IMU. The wind-up, percussive impact, and a subsequent coda wave as a result of scattering from inhomogeneities due to microcracks in the rock are detected in the IMU data. During bite 4 (Figure 20(D)), the change in the drill rotary speed and substrate contact is trackable from the IMU data; observed signals include lowering the drill bit into the existing borehole, beginning active drilling mode, contact with the surface and active drilling, and retraction of the drill out of the borehole. When used in coordination with the host vehicle (e.g., rover, lander) IMU, the TRIDENT seismic source signals can probe subsurface properties with a range much deeper than 1 m. When the current VIPER hardware is remanifested, this experiment will be one that could be undertaken as bonus science on any future mission.

In addition to providing substance material for analysis by two instruments, MSOLO and NIRVSS, the drilling data would significantly impact future lunar mining and ISRU applications. The drill can determine the approximate strength of overconsolidated, ice-rich or ice-cemented subsurface material. For example, if it is found that icy regolith is granular/not cemented and, in turn, relatively weak in nature, a backhoe-type excavation system would be most suitable for excavation. A percussive-type excavation is more suitable if the subsurface material is stronger (e.g., when regolith is compacted) or more cohesive/cemented (A. Green et al. 2013). However, if the subsurface material were found to be extremely hard, a drilling approach similar to another Honeybee drill, Planetary Volatiles Explorer (K. Zacny et al. 2021), would be required, and TRIDENT can adjust its operations to any of these potential conditions.

7. Conclusions

TRIDENT was designed to reach 1 m depths in the lunar subsurface. It operates as part of a rover or static lander payload. It is designed to move subsurface material to the lunar surface, where instruments can analyze the material. During this process, the instrument can make opportunistic science measurements including seismic analysis of near surface while using percussive drilling and determination of compressive strength of subsurface regolith. During operational testing of the drill, measurements on known material have been made so that the comparison to lunar results can be understood, which will lead to a better characterization of the lunar subsurface environment. Future development and testing can result in more capabilities being incorporated into the drill.

TRIDENT represents over two decades of technology development and maturation. Although the PRIME-1 mission landed on its side and VIPER is scheduled to land on the Moon at the end of 2027, the drill can claim several firsts, including the first drill intended to drill into icy soil on the Moon, the first lunar drill to be deployed from a rover, and the first US robotic drill on the Moon.

Acknowledgments

The TRIDENT drill has been developed thanks to funding from various NASA programs such as Small Business Innovation Research, Astrobiology Science and Technology Instrument Development, and Planetary Instrument Definition and Development Program. The project would not have been possible without hard work and dedication from over 200 people over the course of its 20 years of development.

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