A TEST CAMPAIGN TO BASELINE FLIGHT TELEMETRY FOR THE TRIDENT LUNAR DRILL ON PRIME-1 AND VIPER MISSIONS.

I. R. King[1, 2], K. Zacny[1], S. Goldman[1], P. Chu[1], V. Vendiola[1], K. M. Cannon[2], A. Colaprete[3], J. Kleinhenz[4], J. Quinn[5], J. Captain[5], A. Eichenbaum[5] and the TRIDENT team [1]Honeybee Robotics, 2408 Lincoln Ave., Altadena, CA 91001 [2]Center for Space Resources, Colorado School of Mines, 1310 Maple St., GRL 234, Golden, CO 80401 [3]NASA Ames Research Center, Moffett Field, CA 94035, [4]NASA Johnson Space Center, Houston, TX 77058, [5]NASA Kennedy Space Center, Titusville, FL 32899. irking@honeybeerobotics.com

Introduction: Honeybee Robotics has developed The Regolith and Ice Drill for Exploration of New Terrains (TRIDENT) for use in permanently shadowed regions (PSRs) at the base of polar lunar craters. PSRs are known to contain water ice [1], a critical resource in sustaining a human presence on the Moon as intended under NASA's Artemis program. The PRIME-1 lander (launching December 2023) and VIPER rover (launching November 2024) will carry TRIDENT to investigate PSRs for the first time as part of a landed mission.

TRIDENT excavates cuttings from depths up to 1 meter for observation and analysis by lander- and rover-based instruments. However, the drill itself can also be used as an instrument. TRIDENT contains two RTDs and a heater embedded in the auger to carry out thermal measurements. Previous work has also demonstrated that, with appropriate characterization, drill telemetry can predict subsurface material boundary layers in addition to the texture and compressive strength of ice-regolith mixtures [2–4]. This work describes the engineering validation test campaign planned for the TRIDENT engineering unit and how it presents an opportunity to perform this characterization. Three identical TRIDENT units have been built: flight units for VIPER and PRIME-1 (shown in Figure 1) and an engineering unit for this laboratory testing.

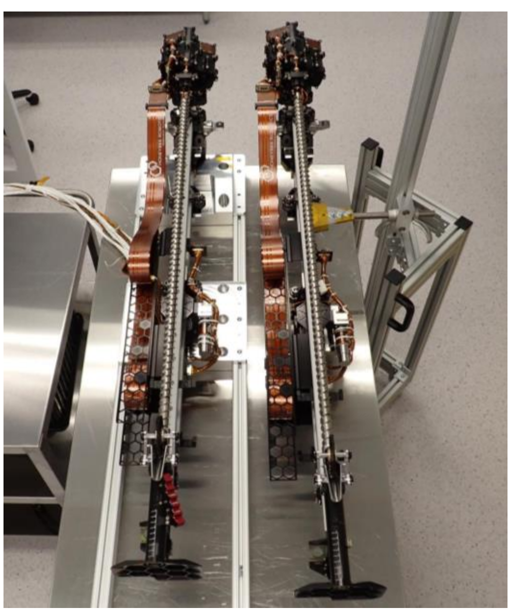

Fig. 1:VIPER (left) and PRIME-1 (right) TRIDENT units.

Test Campaign: The primary goal of the test campaign is to validate TRIDENT engineering requirements such as drill lifetime, drilling speed, and power consumption. Tests will be carried out in environments expected to be representative of lunar PSRs. As such, this test campaign also provides an opportunity to characterize TRIDENT's thermal and drilling feedback in different known material types such that their signatures could be identified from returned lunar telemetry. A high-level test matrix, which is expected to evolve as the test campaign proceeds, is shown in Figure 2.

TEST ID	SUBSTRATE	INCLUSIONS	% WT. H2O	PREP METHOD
1	Limestone	None	0%	--
2	Limestone	None	0%	--
3	NU-LHT-2M	None	0%	Vibratory compacted
4	NU-LHT-2M	None	0%	Vibratory compacted
5	NU-LHT-2M	None	12.0%	Ice cemented
6	NU-LHT-2M	None	8.5%	Ice cemented
7	NU-LHT-2M	None	5.6%	Ice cemented
8	NU-LHT-2M	None	2.7%	Ice cemented
9	Limestone	None	0%	--
10	NU-LHT-2M	None	12.0%	Discrete ice
11	NU-LHT-2M	None	8.5%	Discrete ice
12	NU-LHT-2M	None	5.6%	Discrete ice
13	NU-LHT-2M	None	2.7%	Discrete ice
14	NU-LHT-2M	Typ. Rock Dist.	0%	Vibratory compacted
15	NU-LHT-2M	Typ. Rock Dist.	5.6%	Compacted + ice cemented
16	Limestone	None	0%	--
17	NU-LHT-2M	Typ. Rock Dist.	5.6%	Compacted + discrete ice
18	Colored Plaster	None	0%	Colored layers separated by aluminum foil
19	TBD	--	--	--
20	TBD	--	--	--
21	TBD	--	--	--
22	TBD	--	--	--
23	TBD	--	--	--
24	Limestone	None	0%	--

Fig. 2: High-level test matrix.

The test plan entails drilling 24 holes into several key material types: limestone, dry regolith, ice cemented regolith, discrete ice, rocky regolith, and colored plaster. The lunar simulant used for this testing is NU-LHT-2M. For all simulant tests the mixture is compacted using vibration and the wt. % water is directly measured. The water concentrations to be tested are based on the range of 5.6 ± 2.9 wt. % ice determined by the LCROSS experiment [1]. The majority of tests are performed in a vacuum chamber with a custom-designed bin that will cool simulant to cryogenic temperatures using liquid nitrogen. Five tests are reserved in the plan to allow for repeating tests or creating drilling "challenge cases" at the end of the campaign. The following sub-sections describe the key drilling experiments of the test matrix.

Limestone. Limestone blocks are drilled every 6 holes to control for wear on the bit. These are used because they are homogenous and thus provide a consistent, repeatable drilling resistance. TRIDENT is a rotary percussive drill that only activates percussion in harder materials as determined by the rate of penetration, and limestone tests are known to activate percussion. The two holes drilled into limestone at the start of the campaign will represent an opportunity to tune drilling parameters on a known entity.

Dry regolith. These tests contain only NU-LHT-2M which has been oven-dried to remove moisture. These provide a baseline with which to compare water-doped simulant tests to better identify the signatures of different ice textures and concentrations. Percussion is not expected to be activated during these tests. As with the initial limestone tests, this test is also planned to be run twice for the purpose of tuning drilling parameters.

Ice cemented regolith. This texture of ice-regolith mixture is achieved by mixing water and simulant in a cement mixer, and freezing it inside the simulant bin as described by Kleinhenz and Linne [5]. The result is similar to ice cemented ground found on Earth. Cryogenically frozen ice is extremely hard and therefore these tests, especially at higher ice concentrations, are expected to result in more wear on the drill.

Discrete ice. This texture of ice-regolith mixture is achieved by mixing discrete grains of ice with simulant. To minimize melting and fusing of ice grains this mixing process is performed in a walk-in freezer. This mixture is likely to be mechanically similar to dry regolith alone and is not expected to result in significant wear on the drill. These tests are repeated at the same water ice concentrations as the ice cemented regolith tests to enable a directly comparison of telemetry between the two.

Rocky regolith. These tests introduce rocks with a size distribution described by Cohen et al. [6] to be expected in the top meter of lunar regolith. These include rock sizes between 0.64 and 5 cm diameter. These tests will inform what operational differences can be expected when drilling into homogenous as compared to rocky substrates. As such, they provide insight into how the presence of rocks affects drill telemetry and the extent to which it may obfuscate ice signatures.

Colored plaster. This test is performed to validate that the TRIDENT bite drilling method (excavating only 10 cm of subsurface at a time) maintains subsurface stratigraphy. This method is shown in Figure 3. This test is performed by layering different colors of plaster and excavating one layer at a time. The newly excavated plaster layer should cover the existing cuttings pile.

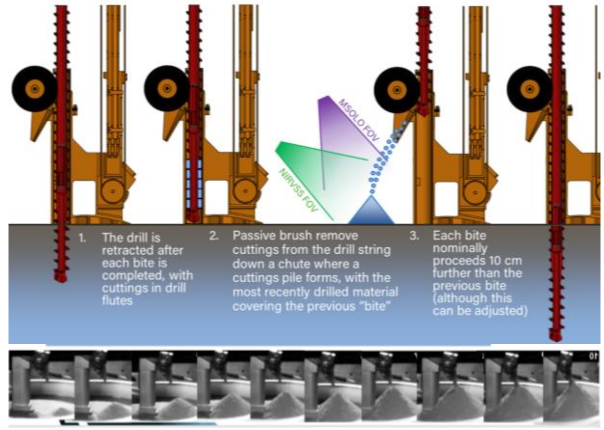

Fig. 3: TRIDENT bite sampling approach. Shown below are cuttings piles from each 10 cm bite down to 1 m.

Conclusion: This test plan has been designed to validate engineering requirements while also establishing a meaningful baseline against which we can compare lunar telemetry. The test plan described here aims to cover different edge cases in mechanical and thermal properties that might be seen in the lunar subsurface. In particular, ice cemented regolith and discrete ice are expected to have different signatures, as are homogenous as compared to rocky mixtures. Given that the texture of the PSR ice-regolith mixture is unknown, it is not only important to demonstrate the drill's ability to operate in all these conditions, but to understand their unique signatures in the telemetry. In doing so, Honeybee Robotics can augment the science return from lander- and rover-based instruments, potentially providing further insight into the texture and mechanical properties of the ice-regolith mixture in lunar PSRs. Using TRIDENT itself as an instrument in this fashion represents a new paradigm of space exploration and resource prospecting.

References: [1] Colaprete A. et al. (2010) *Science*. [2] Zacny K. et al. (2022) *ASCE Earth & Space 2022*. [3] Davé A. et al. (2018) *ASCE Earth & Space 2018*. [4] Joshi D. et al. (2020) *OnePetro*. [5] Kleinhenz J. and Linne D. (2013) *51st AIAA*. [6] Cohen B. A. et al. (2021) *The Planetary Science Journal*.