TRIDENT Drill Performance and Subsurface Fault and Anomaly Detection in Antarctic Environments

Journal: *Annals of Glaciology*

Manuscript ID: AOG-97-0563

Manuscript Type: Article

Date Submitted by the Author: 25-May-2026

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Keywords: Remote sensing, Extraterrestrial glaciology, Lake ice, Frozen ground

Abstract: The Regolith and Ice Drill for Exploring New Terrain (TRIDENT), a 1-meter rotary percussive drill developed by Honeybee Robotics, is designed for extraterrestrial subsurface exploration. Because extraterrestrial drilling cannot rely on prior subsurface characterization or direct human operation, adaptive state estimation and anomaly detection are necessary for reliable autonomous drilling. We evaluate TRIDENT's drilling performance in planetary analog environments during fieldwork in Schirmacher Oasis and Lake Untersee, Antarctica, including cold-desert permafrost terrain, glacially smoothed rock, ice-covered surfaces, subsurface frozen boundary layers, and ice-rock transitions representative of planetary subsurfaces. This paper investigates subsurface fault and anomaly detection methods for planetary drilling

	with minimal prior training data while further characterizing TRIDENT's operational performance across representative analog terrains.

TRIDENT Drill Performance and Subsurface Fault and Anomaly Detection in Antarctic Environments

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ABSTRACT. The Regolith and Ice Drill for Exploring New Terrain (TRIDENT), a 1-meter rotary percussive drill developed by Honeybee Robotics, is designed for extraterrestrial subsurface exploration. Because extraterrestrial drilling cannot rely on prior subsurface characterization or direct human operation, adaptive state estimation and anomaly detection are necessary for reliable autonomous drilling. We evaluate TRIDENT's drilling performance in planetary analog environments during fieldwork in Schirmacher Oasis and Lake Untersee, Antarctica, including cold-desert permafrost terrain, glacially smoothed rock, ice-covered surfaces, subsurface frozen boundary layers, and ice-rock transitions representative of planetary subsurfaces. This paper investigates subsurface fault and anomaly detection methods for planetary drilling with minimal prior training data while further characterizing TRIDENT's operational performance across representative analog terrains.

INTRODUCTION

In January 2026, the NASA Space Technology Mission Directorate (STMD) released civil space technology shortfalls requiring further development to support future missions (S.T.M.D., 2026). Among these priorities is robotic access to subsurface regimes, specifically autonomous deep drilling beyond current capabilities in subsurface regions for pristine or unmodified material.

To investigate this shortfall, this paper focuses on subsurface state and anomaly estimation for an extraterrestrial robotic drill, known as "The Regolith and Ice Drill for Exploring New Terrain" (TRIDENT) (Glass and others, 2023), shown in Figure 1 during fieldwork at Lake Untersee. TRIDENT is a 1-meter rotary percussive drill manufactured by Honeybee Robotics and set as a payload for NASA's 2027 VIPER mission. Autonomous adaptation for extraterrestrial drilling is necessary for long-term, reliable operation. A fundamental constraint on autonomous extraterrestrial drilling is the lack of prior knowledge of the environment and limited ability to estimate state within the borehole. Unlike terrestrial drilling operations, which are typically are informed by prior geological surveys and seismic profiles, extraterrestrial drilling must proceed with essentially no prior subsurface knowledge at the drilling location (Zacny and Cooper, 2006; Boelter and others, 2024).

Drilling at Mars and lunar analog sites on Earth such as Haughton Crater, the Atacama Desert, and Antarctic Dry Valleys has been necessary for development and testing drilling hardware and software, but each field test produces a limited number of fault instances across a narrow range of formation types (Glass and others, 2008, 2023). Even within analog field tests, fault data are costly to obtain, as collecting them requires operating a drill to failure and risking damage to expensive prototype hardware (Glass and others, 2008). As a result, relatively few examples of drilling faults and anomalies are available for training data-driven systems. Although TRIDENT provides telemetry indicators of drilling faults, the scarcity of labeled fault data makes conventional supervised machine learning approaches difficult to apply. This motivates the development of adaptive state estimation and anomaly detection methods capable of identifying abnormal drilling behavior with little to no prior training data before higher-level drilling autonomy can be reliably deployed.

This work further evaluates subspace-based change point detection methods for subsurface fault and anomaly detection first tested in the frost polygon terrain of Haughton Crater in 2025 (Boelter and others, 2026). We evaluate these methods and TRIDENT drill performance in Antarctic planetary analog

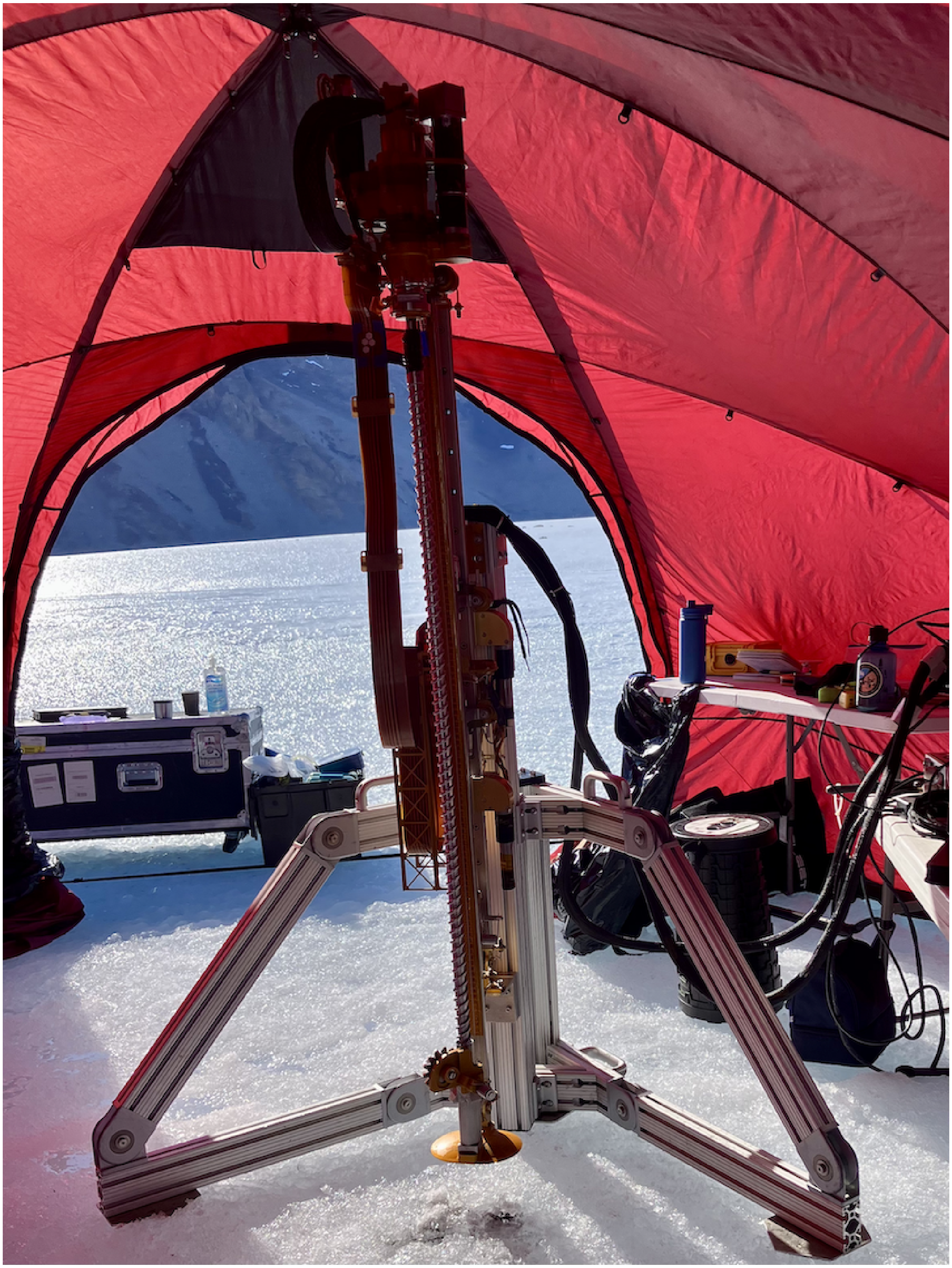

Fig. 1. TRIDENT Drill in Lake Untersee Antarctica.

Table 1. Drill phase space

Variable	Symbol	Description
Torque (Nm)	τ	Force applied by motor for drill string rotation
Auger Velocity (RPM)	ω	Rotational Velocity of the drill string
Rate of Penetration (mm/s)	ρ	Velocity of the drill string relative to Y axis
Weight On Bit (N)	W	Force applied to the bit surface area by the drill string
Depth (m)	D	Depth of drill string from 0-1m

environments. Field testing was conducted in Schirmacher Oasis and Lake Untersee, including cold-desert permafrost terrain, glacially smoothed basement rock, ice-covered surfaces, and ice-rock transition zones representative of planetary subsurfaces. These evaluations provide further context for subsurface fault and anomaly detection for planetary drilling across diverse extraterrestrial analog terrains and further assess the effectiveness of these methods to support the development of autonomous drilling technologies.

INTERPRETING SUBSURFACE DRILLING TELEMETRY

Autonomous drilling requires fast and reliable anomaly and fault detection, which in turn depends on accurately estimating the state of the drill within the borehole and the properties of the surrounding subsurface. However, these conditions are often not directly observable. Instead, borehole conditions, subsurface properties, and drill health must be inferred from telemetry measurements during operation. This creates an inference problem, in which the true internal state of a dynamic system must be estimated from noisy, incomplete, and indirect observations. Telemetry is directly measurable but often noisy due in part to the mechanical vibrations inherent in percussive drilling, and may not fully capture all relevant subsurface interactions (Boelter and others, 2025). Drill telemetry includes parameters such as torque, rate of penetration, weight on bit, and depth (Statham, 2011; Cayeux and others, 2021), described in Table 1. The inference problem is further complicated by the complex and often ambiguous nature of labeling drilling behavior.

Fault types encountered during planetary drilling were first categorized through the DAME project (Glass and others, 2008; Statham, 2011) and are described in Table 2. Detecting these faults without human oversight intelligently necessitates real-time sensing and telemetry of the phase space of the drill as described in Table 1. Measurement of these signals provides the basis for the diagnosis of faults.

Figure 2 shows time-series from two different boreholes. The first shows a normal drilling operation, the

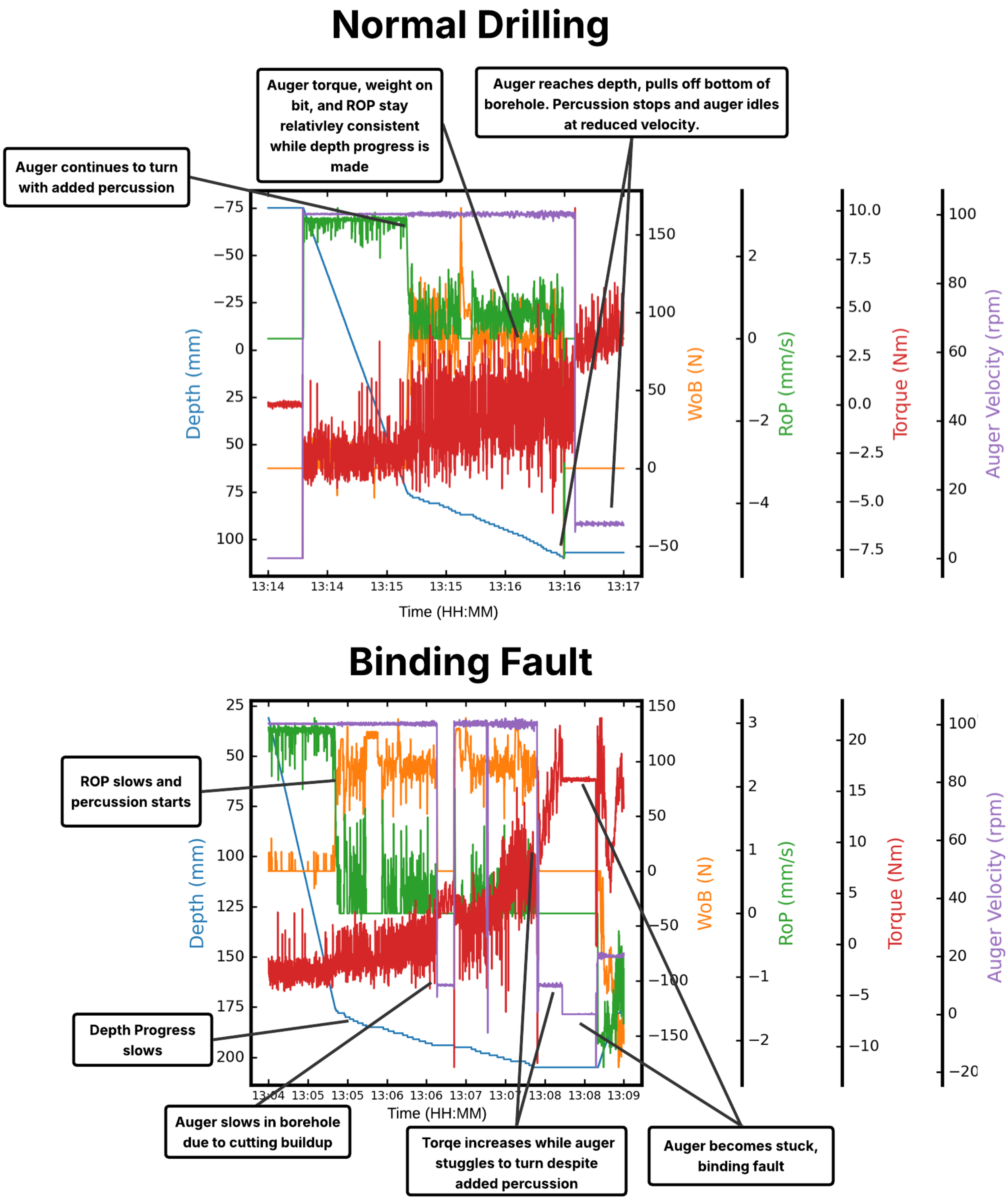

Fig. 2. Time series data showing Depth, Weight on Bit, Rate of Penetration, Auger Velocity, and Auger Torque throughout drilling at incremental bites into composite buckets in our lab. The top image shows normal drilling operations. The bottom image illustrates a binding fault where the Torque and Weight on Bit spike, the Auger Velocity slows, and the auger becomes stuck in the borehole.

Table 2. Fault Types for planetary drilling (Statham, 2011)

Fault Type	Description
Binding Fault	Gravel binds between auger flutes and the borehole wall resulting in increased motor torque (τ).
Choking Fault	Auger flutes are unable to move cuttings upward and out of the borehole fast enough to keep up with the rate of penetration (ρ) resulting in increased τ.
Hard-Materials Fault	Bit encounters unusually hard materials, stalling ρ and driving both weight on bit (W) and τ high.
Corkscrewing Fault	Flutes get caught in a protruding rock, and may cause pulling of the drill string downwards resulting in a negative weight on bit (W).
Bit Inclusion	Gravel is caught between bit and the floor of the borehole resulting in low ρ and high τ.

second illustrates a fault. Generally, faults tend to raise variables like motor Torque τ (the force applied by the motor) while the Rate of Penetration (RoP) ρ (drill string velocity relative to the borehole) is roughly zero. Time series telemetry data of Angular Velocity of the drill string tends to also have sudden dips from getting caught or stuck briefly in the borehole leading up to a fault. In addition to corkscrewing faults and hard materials faults, these time series data points can give us indications of other faults like choking and binding faults. Choking faults occur when excess drill cuttings are not moved up the auger flutes efficiently and cause increased friction between the auger and the borehole wall and binding faults are similar only with gravel getting stuck between auger flutes and the borehole wall. The data is non-static over time, and depending on conditions and situations could span as little as a few seconds to several minutes. From past field experience, faults need to be detected quickly from telemetry symptom onset to mitigate them. Labeling data as faulty or non-faulty is binary in practice, however, the transition from nominal to fault state is gradual rather than instantaneous, which motivates state estimation that tracks the trend of system behavior rather than threshold-triggering on individual measurements.

A BACKGROUND ON EXTRATERRESTRIAL DRILLING

Subsurface Planetary Exploration and Drilling

Early extraterrestrial drilling systems were developed during the Apollo 15, 16, and 17 missions through the Apollo Lunar Surface Drill (ALSD), a handheld rotary-percussive drill designed for astronaut-assisted lunar sampling, while Soviet Luna 16, 20, and 24 missions demonstrated the first autonomous extraterrestrial drilling operations using heavy lander-based platforms (Paulsen and others, 2006). These systems were substantially more massive than modern rover-class platforms, highlighting a longstanding tradeoff in planetary drilling between stability and mobility. Heavy landers provide the reaction force necessary for effective drilling, whereas lightweight rovers enable greater surface exploration but are constrained in achievable weight-on-bit and operational stability (Paulsen and others, 2010; Zacny and others, 2011). This tradeoff has motivated continued research into lightweight drilling systems capable of operating without the stabilizing mass available in terrestrial drilling rigs.

Subsequent planetary missions explored a range of subsurface access strategies under these mobility and mass constraints. The Viking Landers employed robotic scoops for sample acquisition, while the Rock Abrasion Tool (RAT) aboard the Mars Exploration Rovers used grinding rather than drilling to expose shallow subsurface material for scientific analysis. Later missions expanded drilling capabilities through systems such as the Mars Phoenix Lander's Icy Soil Acquisition Device (ISAD), the Mars Science Laboratory rover's miniaturized drill, and the European Space Agency's Rosetta Sampling, Drilling, and Distribution system (SD^2) designed for cometary drilling operations (Zacny and others, 2008). Research on rover-mounted drilling systems initially focused on mobility and hardware design before progressing toward autonomous traversal, sampling, and drilling operations. Carnegie Mellon University's Scarab rover integrated a Northern Centre for Advanced Technology (NORCAT) drill for lunar exploration studies without autonomous drilling capabilities (Bartlett and others, 2008), while later work with the Zoë rover combined a Honeybee Robotics 1-meter rotary percussive drill with autonomous traversal and sampling in Mars-analog testing in the Atacama Desert (Wei and others, 2015).

More recent planetary subsurface exploration research has expanded beyond conventional drilling to include burrowing robots (Liu and others, 2021), legged subsurface exploration platforms such as Lunar Leaper (Kolvenbach and others, 2026), snake-like robotic systems including the Exobiology Extant Life Surveyor (EELS) for exploration of icy moon vents (Vaquero and others, 2024), and remote sensing approaches such as Ground Penetrating Radar (GPR) (Sheppard and Skinner, 2025). Together, these efforts demonstrate a broader shift toward autonomous and adaptive subsurface exploration technologies for planetary environments.

Technological Evolution to TRIDENT

Before discussing the design of TRIDENT and its components, it is important to consider the more than two decades of research and iterative development that led to the current rotary-percussive planetary drill architecture. Planetary drilling systems are subject to stringent design constraints, including low mass, limited power availability (typically below 100 W), strict cleanliness requirements, and the inability to

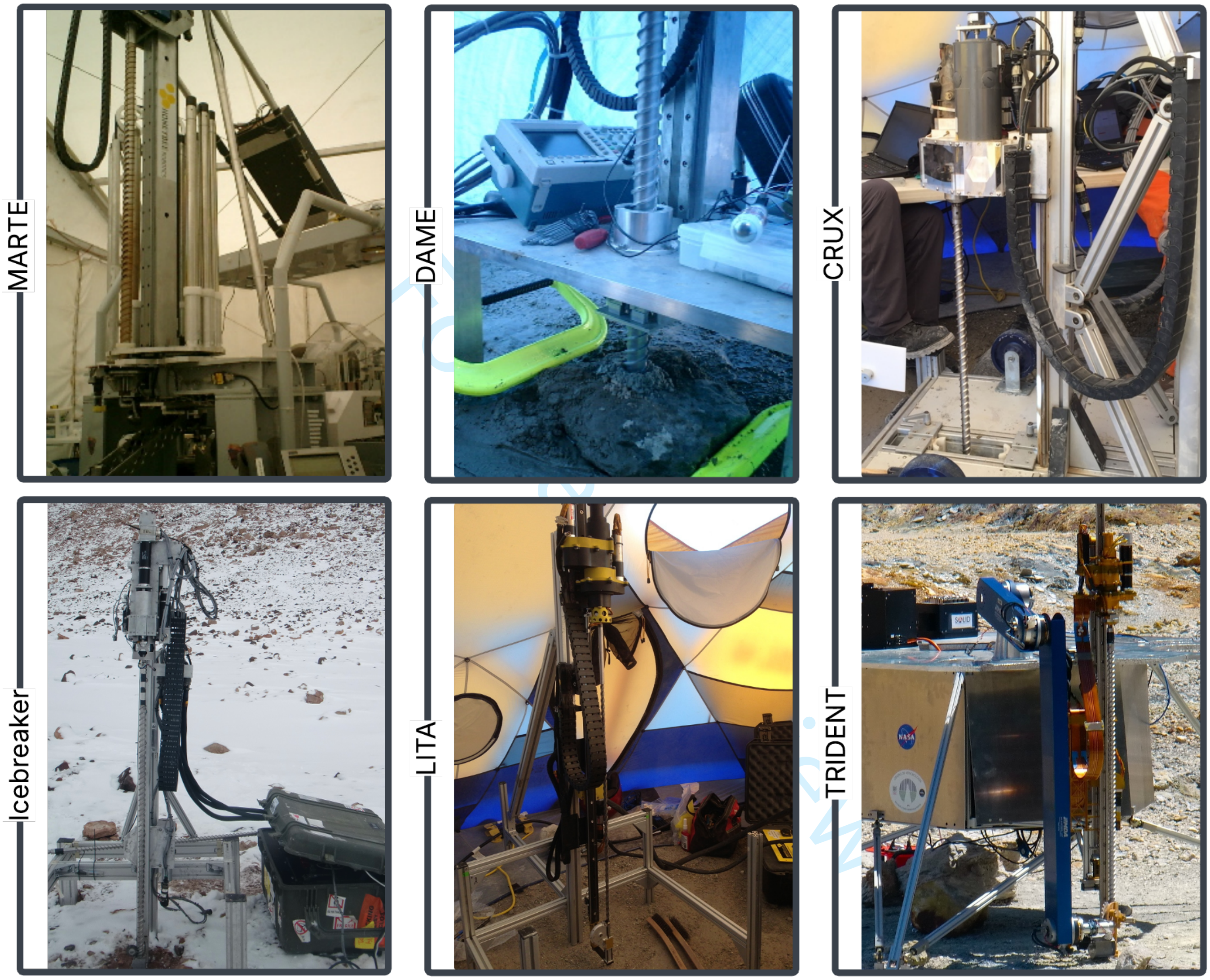

Fig. 3. From top, left to right: MARTE Drill in Rio Tino in 2005, DAME Drill at Haughton Crater in 2004, CRUX Drill 2 at Haughton Crater in 2011, Icebreaker Drill in Antarctica in 2013, LITA Drill in 2013 in Haughton Crater, TRIDENT Drill in Rio Tinto in 2017. Photo Credit B. Glass.

rely on drilling muds or fluids commonly used in terrestrial operations. Additionally, long communication delays and intermittent contact with Earth necessitate highly autonomous in-situ drilling systems capable of reliable operation with minimal human intervention.

Relevant planetary drilling hardware and fieldwork directly preceding TRIDENT include the Mars Astrobiology Research and Technology Experiment (MARTE) drill (Stoker and others, 2004), Drilling Automation for Mars Exploration (DAME) (Glass and others, 2008), the Construction and Resource Utilization eXplorer (CRUX) drill (Zacny and others, 2006), Icebreaker (Glass and others, 2014b), and Life in the Atacama (LITA) drill (Glass and others, 2014a). Each drill is discussed in turn here and is shown in Figure 3. TRIDENT was designed to meet the autonomous operation requirements for the Icebreaker (now Mars Life Explorer) mission (Zacny and others, 2024), at the same time as meeting the physical and power requirements for the VIPER (formerly Resource Prospector) lunar rover mission.

MARTE

The MARTE project (Stoker and others, 2004) project had the objectives of demonstrating drilling technology, sample handling, and instrument technologies needed to search for life in the subsurface biosphere on Mars. The MARTE drilling expedition used commercial coring drills and a planetary prototype drill at a field site within the current Parque Minero de Riotinto in the Rio Tinto River Valley in Southwestern Spain. Drilling in the 2003-2004 seasons was accomplished using a commercial coring drill rig that used water as lubricating fluid. The borehole was drilled to a depth of 166.3 m and core recovery of 98% was achieved for the borehole outside the top 20 m, with these cores subsampled for biosignatures. Initial plans called for the commercial rig to be replaced in 2005 by a 10 m-capable Halliburton-NASA Johnson Space Center lightweight drill design. When the Johnson Space Center team was reassigned in early 2004, the MARTE team instead acquired and modified a DAME drill, adding a carousel with automated string attachment and stowing and core extraction. While too massive to be a practical flight prototype, MARTE drilling at Rio Tinto in September 2005 reached a maximum depth of 7.4 m with its string extensions. At that point, a fouled bayonet attachment failed and part of the MARTE string had to be recovered from resting downhole.

DAME

The DAME drill (Glass and others, 2008) was a Mars-prototype rotary coring drill derived from the 2001 Honeybee Robotics Advanced Deep Drill. The DAME project goals were to demonstrate initial automated drilling into ice lenses and permafrost at a high-fidelity Mars analog site (Haughton Crater on Devon Island, Nunavut). First field tests at Haughton Crater were in the summer of 2004, with subsequent deployments in 2005, 2006, and 2008. A modified second DAME drill unit became the MARTE drill deployed to Spain in 2005. The DAME drill had layered diagnostic and executive software for hands-on and standalone surface operations. Project goals were to conduct manual low-power dry drilling to discover and model the behavior of the drill during problems and faults, take initial software controls and diagnostic models and place them in observation of the drill in the same conditions, and refine and test. Diagnostic approaches included heuristics, neural-net sensor signal processing, and a DeKleerian physics-based simulation compared to live telemetry. These systems voted and communicated via a Common Object Request Broker Architecture (COBRA) middleware layer. DAME reached as deep as 2.3 m at Haughton, but slowly over several days, due to periodic core removals and rotary-only drilling.

CRUX

The CRUX drill (Zacny and others, 2006) was a NASA-funded effort with payload developed by Honeybee Robotics for the exploration of the lunar surface and subsurface with a drill system capable of reaching to a depth of 2 m or more in lunar regolith that was hypothesized to contain frozen water. Concerns regarding DAME and MARTE's slow drilling progress led to a new rotary design for CRUX. Tests were performed with a semi-autonomous drill platform, test chamber, and DAME data acquisition software. Instead of coring, an external auger brought up cuttings from below. In field testing at Haughton Crater (2009-2011), the CRUX drill was 4x faster than predecessor drills reaching 2 m depth into permafrost, and used roughly half as much power doing so. CRUX's 40 kg mass remained marginal for a Mars lander mission or lunar prospector. CRUX was later used again in the ARADS project in 2016 at Haughton and in Chile's Atacama Desert to develop improved Icebreaker Executive (IBExec) control software in anticipation of the arrival of the first TRIDENT unit.

Icebreaker

Robotics and automation for the Icebreaker mission was first discussed in 2006 for missions to Mars. Objectives were to acquire and return samples using a Mars Polar Lander from Lockheed-Martin with life and organics detection instrument payloads, a sample transfer robotic arm, and a 1 m sampling drill (Glass and others, 2014b). In 2010, the rotary-percussive "Icebreaker drill" was a lower-mass and -power iteration from the CRUX design, and was successfully field tested in Antarctica (2011, 2013) and Haughton Crater (2012), including field demonstration of sample transfers from the drill using a robot arm with scoop. The Icebreaker sample acquisition system was tested successfully in Mars chambers and analog field sites to depths between 1 and 3 m. Specific field sites were Haughton Crater on Devon Island in the Canadian Arctic and University Valley in Antarctica.

These field tests showed enough progression in automated drilling and sample acquisition to support consideration of Icebreaker and Icebreaker-like drills in Mars mission proposals submitted to NASA's Discovery program in 2015 and 2019. Tests demonstrated that the Icebreaker integrated subsurface sample acquisition system was capable of remotely operated sample acquisition and delivery to spacecraft deck instruments, in Mars-analog field test environments like Haughton Crater.

LITA

The LITA drill (Cabrol and others, 2005) was a lightweight rotary-percussive drill designed for rover-mounted use by a Carnegie-Mellon and SETI Institute team at the Atacama Desert Chilean analog site in 2010-2011. The LITA drill was much smaller and lighter (10 kg) than previous drills with auger flutes to bring samples to the surface. In 2013-15, the LITA drill design was brought to Haughton Crater for field testing. Main objectives in the Arctic were to test the LITA drill design in the heterogeneous frozen impact breccia at Haughton Crater vs the softer Atacama targets and compare these results as well to the earlier Icebreaker Mars-prototype drill. Test objectives focused specifically on drilling fault modes, the reliability of LITA, and what forces were necessary to apply to make headway into clear ice and ice-cemented materials.

In dry, relatively unconsolidated sediments in Chile LITA performed well; however, LITA did not demonstrate a capability of penetrating hard rock or ice-consolidated material at Haughton Crater. LITA lacked sufficient torque and shaft shear strength to break and penetrate hard rock or ice consolidated material. Once past the dry active layer, the LITA drill could not apply enough torque to avoid binding/freezing once in permafrost.

An attempt was made to upgrade the LITA design with more-capable motors and a stronger drill string. This LITA+ or “Icebreaker-3” version was tested at the Rio Tinto analog site in July 2015 but failed to make progress in hard rocks, experiencing two motor failures. It became clear that Icebreaker would require a more powerful drill design, with some added-back mass and power compared to LITA.

Resource Prospector/VIPER

The Resource Prospector (RP) lunar rover had originally proposed using a rotary drill to be provided by the Canadian Space Agency (CSA); however, this design was neither automated nor light enough for a flight mission. After CSA budget cuts to their planetary surface and robotics programs, they withdrew their support and NASA and RP shifted to Honeybee in the US for the drill. In 2014-16, Honeybee Robotics (Zacny and others, 2024)took the design of the LITA drill system, the LITA field test experience, Icebreaker and RP requirements, and modified the LITA concept for lunar operation for the Resource Prospector (now VIPER) mission. This was a mechanism design and test-heavy effort to select optimum materials for dust abrasion and critical subsystem lifespan, with proper actuator lubrication for low-temperature and vacuum applications. The RP drill was tested beginning in 2017 in lunar-like conditions at NASA Glenn Research Center’s VF-13 chamber, and later with subsequent RP/VIPER rover prototypes at Johnson Space Center. This design was deployed as well to the Atacama Desert on successive tests in 2017-19 on the KREX-2 rover (with Icebreaker instrument payloads) in the ARADS project (Glass and others, 2023). This multipurpose planetary drill design was named the Regolith and Ice Drill for Exploring New Terrain (TRIDENT).

TRIDENT DRILL SUBSYSTEMS

In this section, we will discuss TRIDENT’s hardware and software systems.

TRIDENT Drill Hardware

TRIDENT was developed for regolith and ice acquisition in support of the Volatiles Investigating Polar Exploration Rover (VIPER). TRIDENT incorporates decoupled rotary and percussive mechanisms, enabling three operational modes: rotation, percussion, and combined rotation–percussion. This flexibility allows TRIDENT to both characterize subsurface materials and deliver cuttings to the surface for subsequent analysis by external instruments. The system has a total mass of 19.5 kg (Zacny and others, 2025) and a stowed envelope of 176 cm × 21.5 cm × 27.1 cm. It is designed for survival in extreme thermal environ-

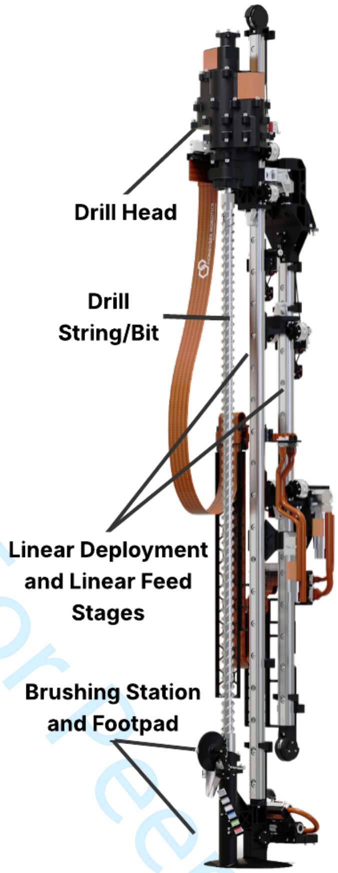

Fig. 4. labeled TRIDENT Drill (NASA Science, 2024)

ments ranging from +70 °C to -233 °C, with operational temperatures between +50 °C and -60 °C when supplemented by onboard thermal control systems (Zacny and others, 2017). TRIDENT is composed of five primary subsystems, as illustrated in Figure 4:

Drill Head: The drill head has a mass of approximately 5 kg and integrates separate mechanisms for rotation and percussion, enabling controlled delivery of both mechanical modes to the drill string. The percussive actuator is rated at 300 W and employs a cam–spring mechanism capable of delivering 2 J per blow at rates of up to 972 blows per minute (Zacny and others, 2017, 2025). This percussive subsystem is engaged as needed to facilitate penetration of high-strength formations, reduce auger torque and binding, and assist in cuttings removal during sample acquisition and delivery. The percussive frequency is also adjustable, allowing adaptation to varying subsurface conditions and mission requirements (Zacny and others, 2025).

Linear Deployment Stage and Linear Feed Stage: Two nested linear stages operating on rolling linear rails are used to enable controlled drill deployment and penetration (Zacny and others, 2025). The deployment stage lowers the drill footpad to the ground and provides an 80 cm stroke, allowing the system to be stowed on a rover deck up to 80 cm above the surface while still achieving ground contact. The feed stage is responsible for advancing the drill string to depths of up to one meter below the subsurface (Zacny and others, 2024). Both stages are rated for 500 N bidirectional (push–pull) loads and employ a cable–pulley transmission architecture, which improves vibration isolation and provides enhanced tolerance to dust contamination in planetary environments (Paulsen and others, 2018).

Drill String/Bit: The drill bit has a diameter of 1 inch (2.54 cm), and the auger length is 119 cm, enabling penetration to depths of at least 102 cm below the surface. This diameter is sufficient to capture an estimated 12 cc of cuttings per 10 cm of depth (Zacny and others, 2017). The auger drill string is composed of two sections: a shorter lower section with deep flutes designed to enhance sample retention by mechanically trapping cuttings and reducing the likelihood of material loss once captured, and a longer upper section optimized for efficient transport of material to the surface for analysis.

Brushing Station and Footpad: The footpad is preloaded against the surface to provide stability during drilling (Zacny and others, 2025). TRIDENT uses a bite-sampling drilling approach in which the bit advances about 10 cm into the subsurface, is then retracted, and the collected cuttings are deposited onto the surface via a rotary brush and chute (Zacny and others, 2025).

Avionics: The avionics system, which includes four Motor Drivers, a Thermal Card, a Power Distribution Unit, and a Command and Data Handling (C&DH) Board, weighs 7 kg. TRIDENT's avionics system includes onboard software, which provides both low-level motor control and high-level logic to control operations (Zacny and others, 2025).

NASA-Developed Drill Software

Icebreaker Executive

Part of the onboard planning and scheduling software, Icebreaker Executive (IbExec), coordinates the control of multiple robotic subsystems. Its capabilities include commanding a robotic arm and robotic drill in coordination with one another (Stucky, 2018). At the core of IbExec is the Plan Execution and

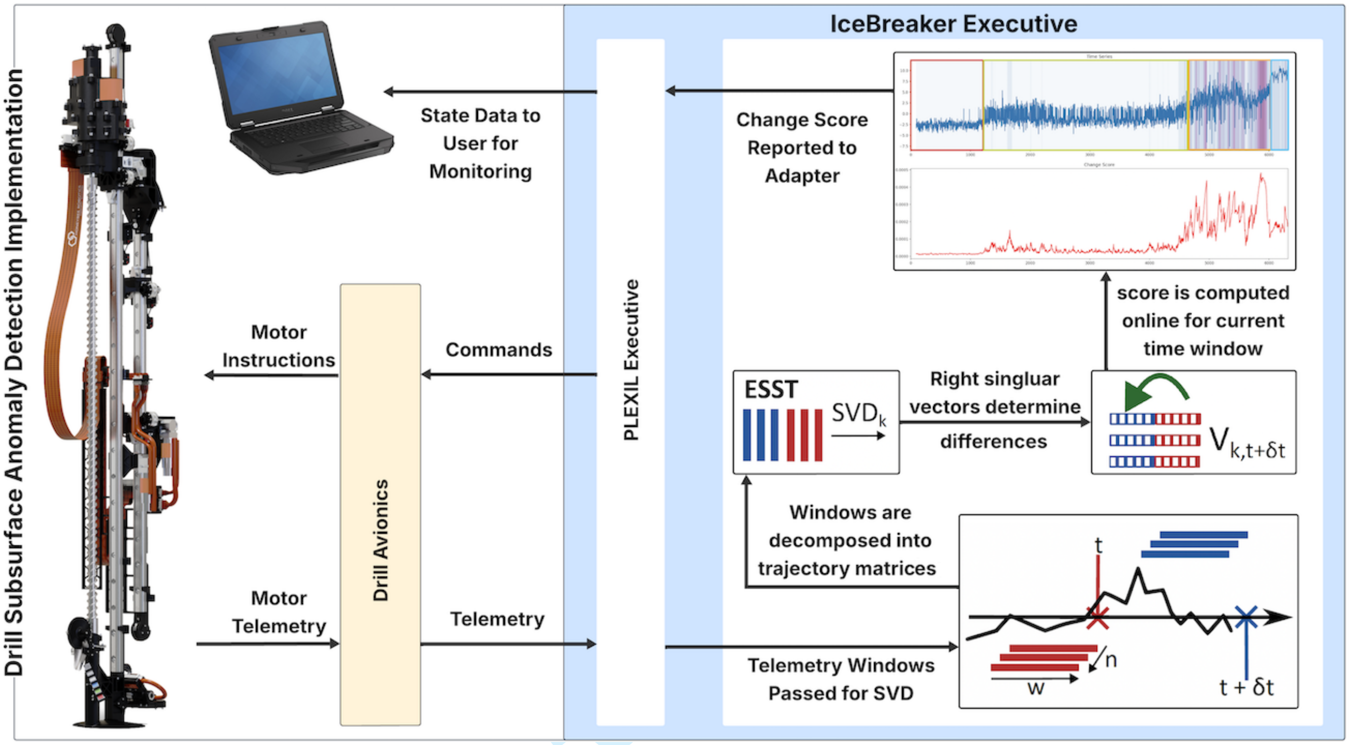

Fig. 5. Drill Subsurface Anomaly Detection Implementation. Motor Telemetry comes into drill avionics. Telemetry is fed to the PLEXIL executive at a rate of 40Hz, and passes windows of data to our ESST Module. The data windows are then decomposed into trajectory matrices, and the right singular vectors determine any significant changes, which are then used to compute the score. The change score for the window is then passed back to the PLEXIL Executive layer to inform decisions making or saved for later analysis. Image adapted from (Boelter and others, 2026)

Interchange Language (PLEXIL), a synchronous reactive language used to write procedures and that enables the extensible hardware interface. The PLEXIL (Dowek and others, 2007) software framework allows for adaptability; its adapter module allows for the swapping of communication methods without the need to alter control scripts. For example, before TRIDENT, the same PLEXIL scripts were used to control two of TRIDENT's predecessor drills, LITA and CRUX, despite all three drills utilizing entirely different communication middleware. The adapter module also enables a multitude of independent systems to be brought together under the same control umbrella, which means PLEXIL can act as a central control executive for an entire mission (Stucky, 2018). TRIDENT uses IbExec as its onboard autonomy software to control payloads. IbExec has helped automate tasks and eliminate user error, however, it still requires constant user oversight and assessment of the environment to select which tasks to do. IbExec currently houses our subsurface fault and anomaly detection software, shown in Figure 5.

Subsurface Fault and Anomaly Detection Software

Our subsurface fault and anomaly detection software uses a subspace-based change-point detection (CPD) method, Enhanced Singular Spectrum Transformation (ESST) (Boelter and others, 2026). Subspace-based CPD methods identify abrupt signal changes without relying on long historical sequences by using signal decomposition rather than explicit statistical modeling, making them effective for detecting transient changes despite limited temporal memory. These methods construct trajectory matrices and apply singular value decomposition (SVD) to extract low-dimensional representations of signal behavior before and after time t, and quantify changes via subspace comparison (Idé and Tsuda, 2007; Moskvina and Zhigljavsky, 2003). Singular Spectrum Transformation (SST) (Idé and Inoue, 2005) computes change scores by comparing singular spectra from consecutive windows, with accelerated variants further improving efficiency (Weber and Lenz, 2025). ESST extends this framework by embedding consecutive windows into a single joint matrix and directly computing change scores, eliminating separate SVD computations and explicit subspace comparison (Boelter and others, 2025, 2026).

Subspace tracking methods extend these ideas to streaming data by monitoring the evolution of low-dimensional subspaces over time. In practice, this efficiently identifies changes in noisy telemetry without supervised training or extensive historical data (Balzano and others, 2018). Subspace-based CPD is thus particularly suitable for drill avionics, where abrupt behavioral changes must be detected robustly under sensor noise. Previous work demonstrated that ESST outperformed SST and other CPD methods on noisy drilling telemetry (Boelter and others, 2026). ESST embeds both past and future subsequences into a single matrix and evaluates whether dominant characteristics are unique to either side of the observation window, allowing future subsequences to contribute directly to the final change score. We analyze the k dominant right singular vectors V_k of the two-sided Hankel matrix, where the first half of the columns correspond to subsequences centered at time t and the second half correspond to subsequences centered at $t + \delta t$:

$$\tilde{S} * T^t = \frac{\sum *i = 0^{k-1}\sigma_i \ \left|\frac{1}{N}\left(\sum_{j=0}^{n/2-1} V^{i,j} - \sum_{j=n/2}^{n-1} V^{i,j}\right)\right|}{\sum_{i=0}^{k-1}\sigma_i}. \tag{1}$$

Using multiple singular vectors provides a more complete representation of the time series. ESST enables this by modifying the Hankel matrix construction and leveraging the previously unused right singular vectors $V_{t,k}$. The method parameters include the subspace rank k, the number of sequences n, the subsequence length w, and the separation δt between windows. For the Antarctic field exercise, we fixed $\delta t = w/3$ and selected $k = 5$ based on prior work. A window size of $w = 70$ provided accurate online fault and anomaly detection for telemetry sampled at 40 Hz.

Incoming faults are often preceded by increased motor torque τ or decreased rate of penetration ρ (Boelter and others, 2026). Increases in weight on bit W and sudden drops in auger angular velocity ω can also indicate fault onset. We formulate the problem as an online CPD problem across signal, detection, and operational layers.

At the signal layer, telemetry streams at $f_s = 40$ Hz and is represented as:

$$\mathbf{x}(t) = \Big[x^{(\tau)}(t)\ x^{(\rho)}(t)\ x^{(\omega)}(t)\Big] \in \mathbb{R}^4, \tag{2}$$

where $x^{(\tau)}(t)$ is motor torque, $x^{(\phi)}(t)$ is weight on bit (WoB), $x^{(\rho)}(t)$ is rate of penetration (ROP), and $x^{(\omega)}(t)$ is auger angular velocity. Each channel is normalized online using a sliding buffer B:

$$\tilde{x}^{(c)}(t) = \frac{x^{(c)}(t) - \mu_B^{(c)}}{\sigma_B^{(c)} + \epsilon}, \quad c \in \tau, \rho, \omega. \tag{3}$$

Sliding windows of length w are embedded into trajectory matrices $\mathbf{H}*t$ and decomposed using truncated SVD. For each channel c, the ESST change score is computed using Eq. 1, where $\overline{v}*i,\text{past}^{(c)}$ and $\overline{v}_{i,\text{future}}^{(c)}$ denote the means of the first and second halves of the right singular vector $\mathbf{v}*i$. The fused multivariate score is:

$$S_t = \sum *c \in \tau, \rho, \omega w_c S_t^{(c)}, \quad w_c \geqslant 0, \quad \sum_c w_c = 1. \tag{4}$$

The anomaly score S_t links telemetry to fault detection thresholds. For a true fault onset at time $t^\star$, the detection delay is:

$$\tau_{\text{detect}} = \min \Delta t \geqslant 0 : S_{t^\star + \Delta t} \geqslant \theta. \tag{5}$$

At the operational layer, drilling efficiency depends on both nominal drilling time and delays associated with fault detection and mitigation. Let T_{nominal} denote the expected drilling time without faults, F the set of possible faults, $P(f)$ the probability of fault $f \in F$, $\tau_{\text{detect}}(f)$ the mean ESST detection delay, and $\tau_{\text{mitigate}}(f)$ the mean mitigation time. The expected drilling time is:

$$\mathbb{E}[T_{\text{drill}}] = T_{\text{nominal}} + \sum_{f \in F} P(f)\Big(\tau_{\text{detect}}(f) + \tau_{\text{mitigate}}(f)\Big). \tag{6}$$

Reducing $\tau_{\text{detect}}(f)$ directly lowers expected drilling time, highlighting the operational value of ESST-based fault detection.

The ESST fault detection algorithm was previously tested on TRIDENT using recorded telemetry (Boelter and others, 2025). During integration with the drill avionics through PLEXIL at ~ 40 Hz, we encountered a trade-off between lower-rate sampling with occasional gaps and higher-rate sampling with potential duplicates. Due to planetary computational constraints, we selected lower-rate sampling and validated ESST under skipped time steps. As shown in Figure 5, the drill avionics pass motor telemetry to the PLEXIL Executive, which sends incremental data windows to the ESST module. These windows are decomposed into trajectory matrices, and the resulting right singular vectors are used to detect significant changes and compute a change score for operator evaluation (Boelter and others, 2026).

ANTARCTIC DRILLING SITES

In January 2026, an interdisciplinary team conducted drilling site selection in Antarctica, targeting locations with environmental and geological characteristics analogous to those expected for Mars lander and rover missions. Both Schirmacher Oasis and Lake Untersee have previously been employed as Mars analog environments in prior studies.(McKay and others, 2017; Hoover, 2008; Wagner and others, 2019). Three locations in Schirmacher Oasis in Queen Maud Land were chosen for their cold-desert, ice-free Mars-analog location, with permafrost found at 20-30 cm of depth and featuring geomorphic processes and microbial thermophiles. The long-term stable hard ice covering Lake Untersee was also a selected drilling test site. Lake Untersee is permanently sealed beneath a thick ice cover (around 2–3 meters), which never melts (Faucher and others, 2019). This creates a closed, isolated system that is useful as an astrobiology analog because it mimics the ice-covered oceans hypothesized on Europa and Enceladus, two of the most promising targets in the search for extraterrestrial life. The surface ice of Untersee also develops distinctive conical pits and ablation features shaped by sublimation and wind erosion rather than melting. Table 3 summarizes the drilling sites chosen.

Our objectives were to study TRIDENT's performance in icy subsurface analog regions. Given previous experience in Arctic impact crater drilling, we aimed for subsurface analog regions in two apparent glacial-smoothed basement areas (Sites 1 and 3). Adjacent ice bodies overlapping these would then allow us to test TRIDENT drilling and software performance going through ice-rock material transitions (Sites 2 and 4). The centuries-old hardened permanent Lake Untersee surface ice over water (Site 5) was an attractive

Fig. 6. Antarctic Map from the United States Antarctic Program (United States Antarctic Program, 2000) with Schirmacher Oasis and Lake Untersee labeled.

Table 3. Antarctica TRIDENT Drilling Tests January 2026

Site	Area	Coordinates	Characterization	Cum. Depth (m)	Objective/Target
1	Schirmacher Oasis (shown in Figure 7)	S70.77545, E11.82644	Gneissic stoss and lee knob, centered location	2.18	Thawed/frozen subsurface boundary
2	Schirmacher Oasis	S70.77564, E11.85382	Stoss or upstream side of Site 1, edge with covering ice	2.53	Ice over rock interface
3	Schirmacher Oasis	S70.77351, E11.84345	Gneissic planar surface adjacent to ice	1.84	Thawed/frozen subsurface boundary
4	Schirmacher Oasis	—	Edge of ice cover for Site 3	NA	Ice over rock interface*
5	Lake Untersee	S71.33069, E13.50706	Permanent lake ice cover	2.4	Frozen lake cover
6	Oasis Base Camp	S70.77525, E11.83809	Slope of glacial-deposited basement rocks	0.13	Heterogeneous gneissic slope surface rocks

Fig. 7. Drilling into thawed/frozen subsurface boundary in Schirmacher Oasis in Antarctica. Photo credit B. Glass.

analog both for Ocean Worlds (e.g., Enceladus, Titan, Europa) and future Mars near-surface ice drilling.

Weather conditions and flight logistics led to both Site 5 moving up and a shorter field stay than planned, so Site 4 was not drilled. A desire to generate additional drilling faults led to drilling on pull-out day into a rocky glacial till slope near the Oasis basecamp (Site 6).

TRIDENT ANTARCTIC EXPERIMENTS AND RESULTS

In this section, we evaluate subsurface fault and anomaly detection performance and assess TRIDENT's operation across the field sites listed in Table 3. Telemetry data was collected from fifteen boreholes distributed across five sites (1,2,3,5, and 6). However, owing to a failed over-the-air software update, the standalone fault and anomaly detection system monitored only the final eight boreholes at Sites 3, 4, and 6. Additionally, field operations experienced downtime due to failure of the percussive spring assembly.

Subsurface Anomaly Detection Software

This section assesses our subsurface fault and anomaly detection software in the Antarctic and compare its performance to previous field seasons. For evaluation purposes, it is important to note the data collection and fault labeling protocols. Time series telemetry data were collected in the field by the fault and anomaly detection software during drilling operations. Concurrently, handwritten notes were recorded to document changes in drill behavior and other anomalies, including auger pauses in the borehole, motor strain, squeaking noises from the auger, lack of drilling progress, and suspected faulty behavior. Data were labeled in a binary manner (faulty or non-faulty) using the timestamps from these notes in conjunction with visual inspection of graphed telemetry datasets.

We use standardized mean difference (SMD) to quantitatively compare these labeled datasets across drilling events and field seasons. SMD quantifies the magnitude of difference between two groups and is widely used in meta-analyses to compare datasets with differing scales, units, or methodologies (Andrade, 2020). This makes SMD particularly well suited to this use case, where telemetry and performance metrics vary in scale and the drilling material properties are unknown. Specifically, we use Cohen's D, which computes a unitless D value using the pooled standard deviation. Conventionally, values of ± 0.2 indicate a small effect size, while values of ± 0.8 or greater indicate a large effect size.

Antarctic Fault and Anomaly Detection Results

For our fault and anomaly detection software, for our parameters for Equation 1, we fixed $\delta t = w/3$ with window size $w = 70$ and $k = 5$. These parameters provided accurate online fault and anomaly detection for telemetry sampled at 40 Hz both in the lab and Haughton Crater.

Field testing in Schirmacher Oasis and Lake Untersee examined subsurface fault and anomaly detection across Antarctic analog terrains. Because each borehole is different and may produce metrics that differ in scale, a standardized effect-size measure is required to compare results consistently. We therefore use the SMD as in Boelter and others (2026).

We calculated SMD scores for our Antarctic field results, shown in the bottom row of 8 and in the rightmost column in Table 4. All datasets except τ value had a Cohen's D score greater than ± 0.8, indicating the faulty telemetry data for most of our datasets had a significant difference from our non-faulty telemetry data. The results from ρ score, τ score, and τ telemetry value indicate that our method for subsurface anomaly and fault detection is effective across analog environments with diverse subsurface composition.

We also decided to monitor a new telemetry stream in the Antarctic, Auger Velocity (ω). In our lab testing and at Haughton Crater, we observed instances in which the auger slowed or temporarily paused during drilling; this telemetry value was not assessed in the lab or at Haughton Crater by our fault and anomaly detection software. A paused auger may indicate bit inclusion or cuttings accumulation within the borehole, both of which can increase frictional resistance along the borehole wall and degrade drilling efficiency. In our Antarctic field work, we expanded the range of telemetry monitoring by our subsurface fault and anomaly detection software to include ω to better characterize faulty drill behavior.

We assessed ω for the duration of the Antarctic fieldwork during faulty events. Figure 9 shows several instances of ω telemetry during drilling at Site 5. Of note, the middle graph of 9 correlates with the torque graph from Antarctic fieldwork shown in the bottom right corner of Figure 8. From our observations, the ESST algorithm successfully detected several instances where the ω slowed of stopped turning entirely during a fault. We also found our ω value and score had Cohen's D scores consistently above ± 0.2 indicating the faulty telemetry had a slight difference in score from the non-faulty telemetry.

Detecting faults and anomalies in τ (noisy percussive telemetry with subtle anomalies) versus ω (straightforward telemetry with a sudden shift in the mean). In the field of changepoint detection, the latter problem is very simplistic in nature, and most simple subspace-based CPD programs could assess the

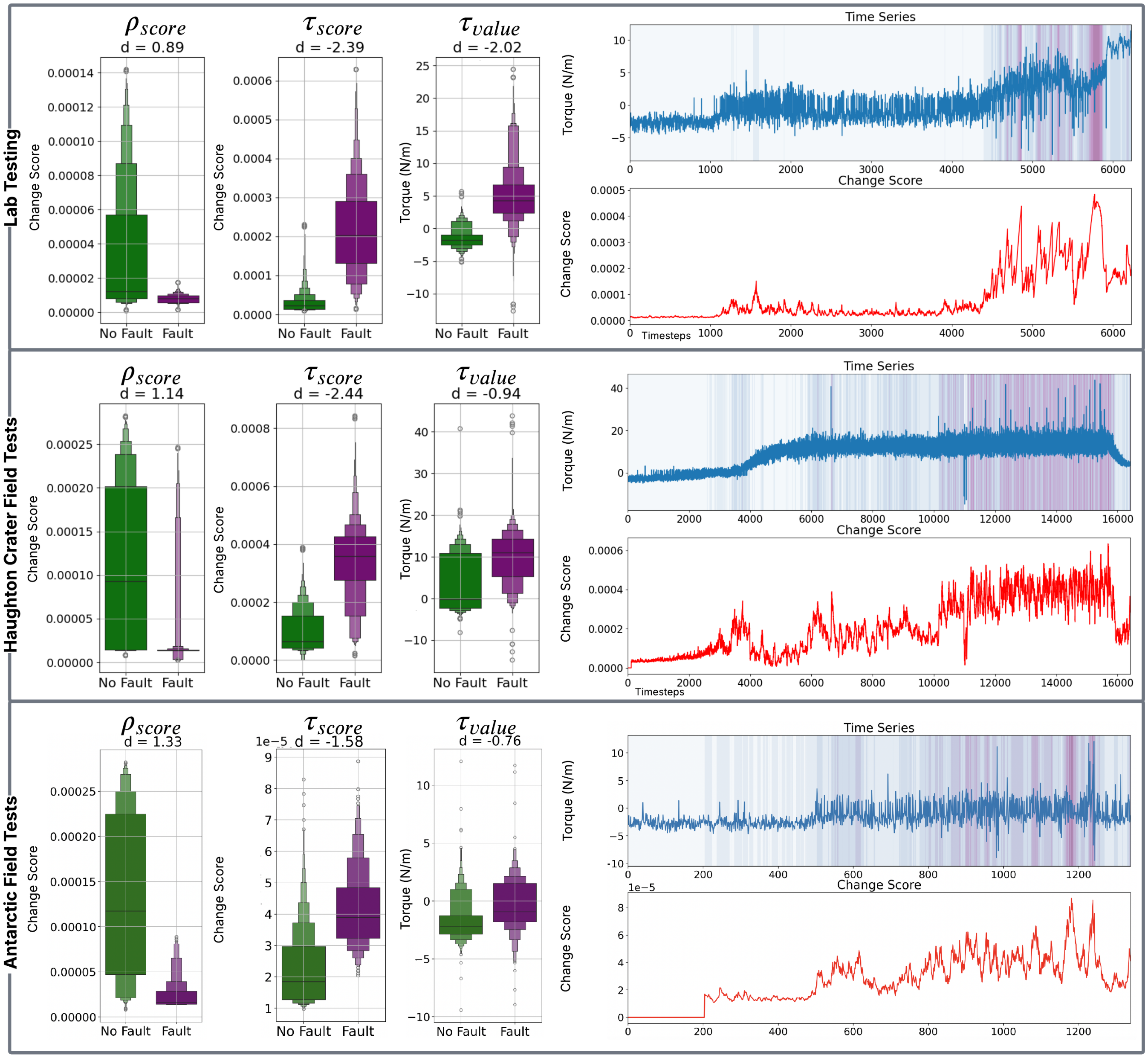

Fig. 8. Results from: (top) fault induced during lab testing, (middle) fault encountered at Haughton Crater Analog site during field testing, and (bottom) fault encountered at Antarctic field testing. Left-side results show score distributions with and Cohen's D score showing the degree of difference between faulty and non-faulty datasets. Right-side results show motor torque τ time series data graphed over the course of a fault (blue line) with the corresponding online change score (red line). The purple shading in the right-hand graphs indicate the severity of the change score, with the severity increasing with the buildup to the fault. Lab and Haughton Crater results taken from (Boelter and others, 2026).

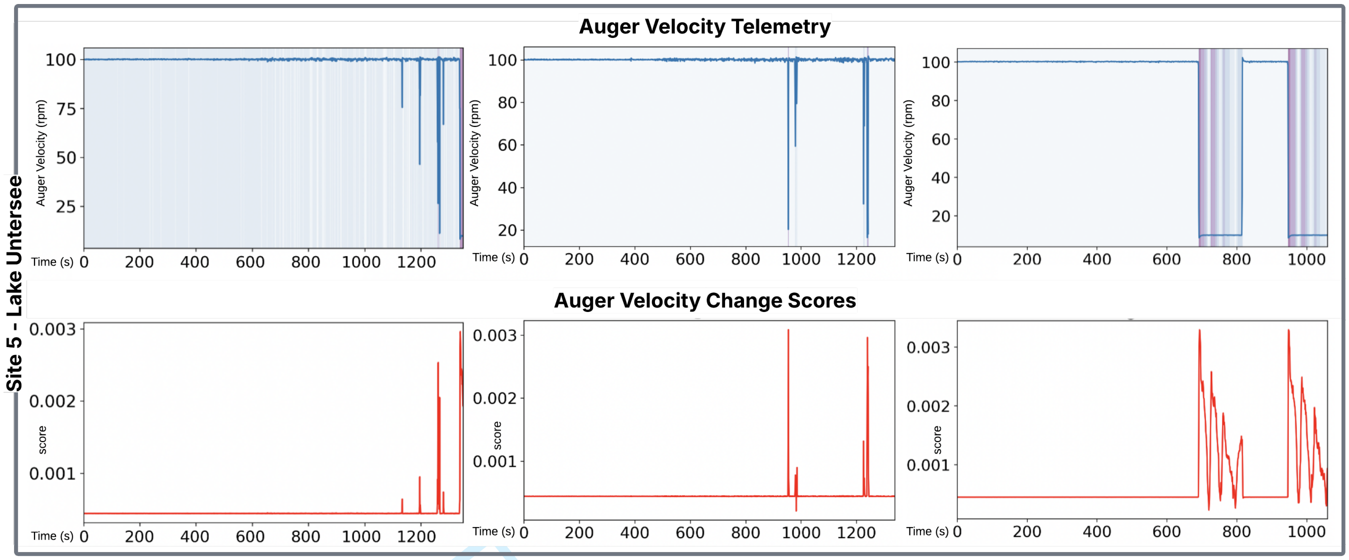

Fig. 9. Auger velocity (ω) telemetry and respective change scores at noted faulty events at Site 5 - Lake Untersee. The middle graph correlates with the torque graph from Antarctic fieldwork shown in the bottom right corner of Figure 8

change point in the ω telemetry trivially. Here, we use ESST because adding another monitored telemetry stream is more straightforward than validating and tuning a different monitoring methodology. We found the performance of the algorithm did not change noticeably by adding an additional telemetry stream.

Comparison to Previous Field Results

While this paper focuses on Antarctic Field Tests, it is important to note we evaluated our fault and anomaly detection software in a lab environment with buckets of composite materials designed to trigger faulty conditions, and at Haughton Crater (Boelter and others, 2026). The Haughton Impact Structure is a 23 km-wide impact crater and well-studied Mars analog site due to its cold, dry environment and polygonal terrain resembling Martian high latitudes (Osinski and others, 2005; Barfoot and others, 2010b; Furgale and others, 2012; Barfoot and others, 2010a). We compare our subsurface anomaly detection software results to our lab tests and Haughton crater to give a holistic representation of how our software has performed in different analogs against the same telemetry streams.

Our SMD scores for our lab and Haughton Crater field test values are shown in the top two rows in Figure 8 and in the middle two columns in Table 4. These datasets had Cohen's D score greater than ± 0.8, indicating the faulty telemetry data for most of our datasets had a significant difference from our non-faulty telemetry data. This also shows our Antarctic fault and anomaly detection results are consistent

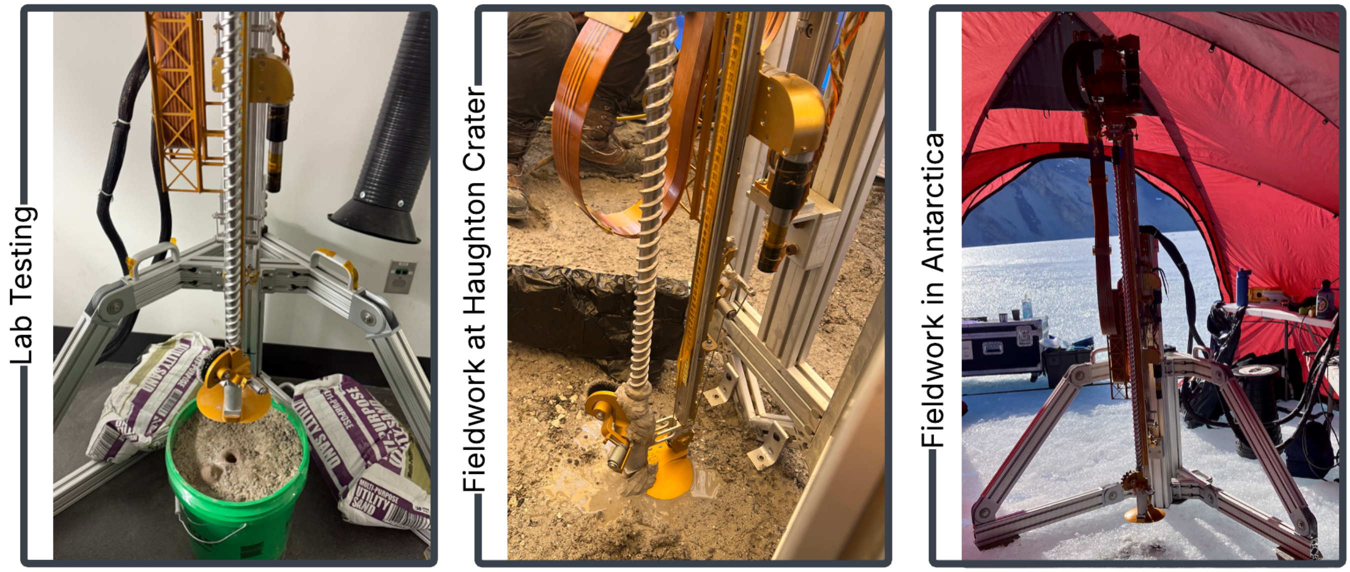

Fig. 10. Left: lab testing using regolith simulant buckets designed to quickly induce faults. Middle: drilling up to 1 m at Haughton Crater in August 2025. Right: drilling up to 1 m at Lake Untersee, Antarctica in January 2026.

Table 4. SMD Cohen's D Value for all results. ω was not monitored in the lab or at Haughton Crater.

Value	**Dataset Cohen's D Value**		
Location	**Lab**	**Haughton Crater**	**Antarctica**
τ value	-2.02	-0.94	-0.76
τ score	-2.39	-2.44	-1.58
ρ score	0.89	1.14	1.33
ω value	–	–	0.26
ω score	–	–	0.25

with previous analog field tests.

TRIDENT Drill Performance

Drill Performance Comparison by Depth

Subsurface information can be estimated from drill telemetry aligned in depth-series order, such as locations of material horizons and material composition. Multiple boreholes were drilled across five sites with three target material characterizations: subsurface rock boundary (Sites 1 and 3), ice-rock strata transitions (Site 2), and frozen lake cover (Site 5). Two sample boreholes from each of these three categories are discussed

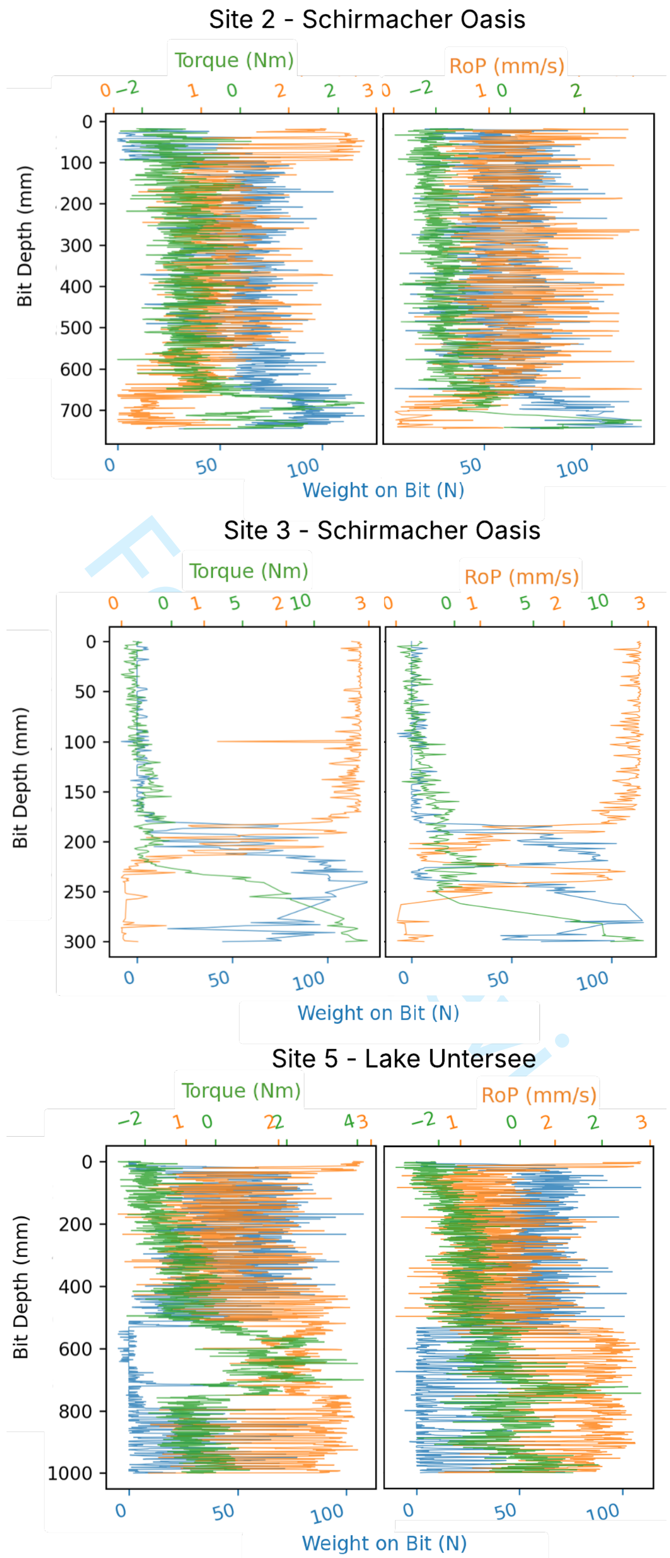

Fig. 11. Top graphs are Site 2 in Shirmacher Oasis showing drilling to 70 cm in ice over rock interface. Middle Graphs shows Site 3 in Shirmacher Oasis drilling into thawed/frozen subsurface boundary. Bottom graphs are Site 5 at Lake Untersee drilling into Frozen Lake.

below.

At Site 2, the selected boreholes show an increase in auger torque and weight on bit accompanied by a decrease in rate of penetration at a depth of approximately 62 cm, consistent with an ice-rock transition (Figure 11). The selected boreholes located at Site 3 drilled through weak glacial till, which became gravelly as the depth increased, before reaching a frozen subsurface boundary at 20 cm, indicated by a stark decrease in rate of penetration and increase of torque and weight on bit 11. At Site 5 at Lake Untersee, the boreholes showed a rapid decrease in weight on bit coupled with an increase of rate of penetration at 50 cm. Previous research has documented the bubble content of the lake's ice cover is greatest in the upper 75 cm, peaking at 54 cm Faucher and others (2019). This correlates with the extreme telemetry changes seen in 11 for Site 5, as bubbles (air pockets trapped in the ice) are much weaker than solid ice.

Telemetry indicative of ice drilling can be seen in the first 50 cm of Site 2 and Site 5, where all three parameters oscillate widely and rapidly while remaining largely centered. In comparison, telemetry indicative of soil and other softer materials is seen at Site 3, with torque and weight on bit remaining consistently low and rate of penetration remains consistently high. Harder materials, such as rock and frozen soil, result in rapidly-decreasing rate of penetration accompanied by increased torque and weight on bit as seen above the 50 cm depth of Site 2 and 20 cm depth of Site 3.

Broken Percussive Spring

Spaceflight qualification of TRIDENT's design required multiple test-to-failure examples performed by Honeybee Robotics. In these, the cam-spring percussive head was observed to eventually fail from metal fatigue after 2-3 days of continual percussive drilling. This was sufficient as the flight requirement for cumulative drilling duration on TRIDENT was an order of magnitude smaller. However, the engineering unit used for field testing had been in research use since 2016 and had drilled roughly 80-90 m in its lifetime. Following summer 2025 Haughton crater tests, lab benchmarks at the University of Minnesota indicated an intermittent percussion lockup that cleared itself. Inspection at Honeybee did not show a failure, so the unit was shipped to Antarctica where it was operated for two days before a broken spring on 24 January at site 2 required disassembly and overhaul in the field; however, spares had been brought and the TRIDENT returned to use the following day. Figure 12 shows the broken spring and 13 shows the replaced percussive spring.

Fig. 12. Broken percussive spring

Fig. 13. Replacement for broken percussive spring.

CONCLUSIONS

We experienced both an instance of broken drill hardware, a broken primary computer, and software bugs that required on-site hardware repair and over-the-air remote developer software fixes via satellite to remote field sites in Antarctica. This reflects the dynamic and unpredictable nature of field robotics, the level of hardware and software preparation and redundancy required for successful operation, and the breadth of skills needed to address issues. Despite these challenges, the successful data collection and subsequent method evaluation during this field season represents significant operational achievement, highlighting the robustness of both our experimental design and the contingency measures for addressing hardware and software failures in remote, extreme environments while evaluating experimental and untested methods.

This work further evaluated subspace-based change-point detection methods for subsurface fault and anomaly detection, originally demonstrated in the frost polygon terrain of Haughton Crater in 2025 (Boelter and others, 2026), and assesses their performance alongside TRIDENT in Antarctic planetary analog environments. Overall, for real-world field datasets, we consider the antarctic results from the fault and anomaly detection software to be a success. The results provide additional validation of these methods for identifying faults and anomalous drilling behavior across diverse and geologically varied analog terrains, while also characterizing TRIDENT's operational response under realistic subsurface variability. As we begin development for autonomous drilling methodologies, we will continue to monitor and evaluate the performance of this software in both laboratory and field settings, and future work will focus on improving integration of subspace-based anomaly detection within autonomous drilling systems to support robust state estimation and fault-aware operation in planetary exploration scenarios.

ACKNOWLEDGEMENTS

This work was supported by NASA Ames Drilling in Goddard Institute Field Team and the Minnesota Space Grant Consortium.

REFERENCES

Andrade C (2020) Mean difference, standardized mean difference (smd), and their use in meta-analysis: As simple as it gets. *The Journal of Clinical Psychiatry*, **81**(5), 11349 (doi: 10.4088/JCP.20f13681)

Balzano L, Chi Y and Lu Y (2018) Streaming PCA and subspace tracking: The missing data case. *Proceedings of the IEEE*, **PP** (doi: 10.1109/JPROC.2018.2847041)

Barfoot TD, Furgale PT, Osinski GR, Ghafoor N and Williams KK (2010a) Field testing of robotic technologies to support ground ice prospecting in martian polygonal terrain. *Planetary and Space Science*, **58**(4), 671–681, ISSN 00320633 (doi: 10.1016/j.pss.2009.09.021)

Barfoot TD, Furgale PT, Stenning BE, Carle PJF, Enright JP and Lee P (2010b) Devon island as a proving ground for planetary rovers. In J Angeles, B Boulet, JJ Clark, J Kövecses and K Siddiqi (eds.), *Brain, Body and Machine*, 269–281, Springer Berlin Heidelberg, Berlin, Heidelberg, ISBN 978-3-642-16259-6

Bartlett PW, Wettergreen D and Whittaker WRL (2008) Design of the scarab rover for mobility and drilling in the lunar cold traps. In *Proceedings of the International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS '08)*, 3–6 (doi: 10.1184/R1/6552563)

Boelter S, Temesgen E, Glass B and Gini M (2024) Understanding drill data for autonomous application. In *International Workshop on Autonomous Agents and Multi-Agent Systems for Space Applications at AAMAS*

Boelter S, Weber L, Lenz R, Glass B and Gini M (2025) Fault prediction in drilling using subspace analysis techniques. *Intelligent Autonomous Systems 19, Proc. 19th Int'l Conf IAS-19, in press*

Boelter S, Brown G, Weber L, Stucky T, Glass B and Gini M (2026) Model-free subsurface anomaly detection using subspace analysis techniques for sparse telemetry for extraterrestrial drilling robots. *Proc. IEEE Int'l Conf. on Robotics and Automation (ICRA), in press*

Cabrol NA, Wettergreen DS, Whittaker R, Grin EA, Moersch J, Diaz GC, Cockell C, Coppin P, Dohm JM and Fisher G (2005) Searching for life with rovers: Exploration methods & science results from the 2004 field campaign of the "life in the atacama" project and applications to future mars missions. In *Lunar and Planetary Science XXXVI, Part 3*, Lunar and Planetary Institute

Cayeux E, Daireaux B, Ambrus A, Mihai R and Carlsen L (2021) Autonomous decision-making while drilling. *Energies*, **14**, 969 (doi: 10.3390/en14040969)

Dowek G, Muñoz CA and Pasareanu CS (2007) A formal analysis framework for PLEXIL. In *Workshop at ICAPS*

Faucher B, Lacelle D, Fisher DA, Andersen DT and McKay CP (2019) Energy and water mass balance of lake untersee and its perennial ice cover, east antarctica. *Antarctic Science*, **31**(5), 271–285 (doi: 10.1017/S0954102019000176)

Furgale P, Carle P, Enright J and Barfoot TD (2012) The Devon Island rover navigation dataset. *The International Journal of Robotics Research*, **31**(6), 707–713, ISSN 0278-3649, 1741-3176 (doi: 10.1177/0278364911433135)

Glass B, Cannon H, Branson M and Hanagud S (2008) Dame: Planetary-prototype drilling automation. *Astrobiology*, **8**(3), 653–664 (doi: 10.1089/ast.2007.0148)

Glass B, Wang A, Huffman1 S, Zacny K and Lee1 P (2014a) Lita drill tests at haughton crater. *45th Lunar and Planetary Science Conference 2014*

Glass B, Bergman D, Parro V, Kobayashi L, Stoker C, Quinn R, Davila A, Willis P, Brinckerhoff W, Warren-Rhodes K, Wilhelm M, Caceres L, DiRuggiero J, Zacny K, Moreno-Paz M, Dave A, Seitz S, Grubisic A, Castillo M, Bonaccorsi R and the ARADS Team (2023) The Atacama rover astrobiology drilling studies (ARADS) project. *Astrobiology*, **23**, 1245–1258 (doi: https://doi.org/10.1089/ast.2022.0126)

Glass BJ, Dave A, McKay CP and Paulsen G (2014b) Robotics and Automation for “Icebreaker”. *Journal of Field Robotics*, **31**(1), 192–205, ISSN 1556-4959, 1556-4967 (doi: 10.1002/rob.21487)

Hoover R (2008) Schirmacher oasis/lake untersee antarctica astrobiology expedition expedition report flag 162. Technical report, United States Space and Rocket Center (doi: 10.13140/RG.2.2.18427.39200)

Idé T and Inoue K (2005) *Knowledge Discovery from Heterogeneous Dynamic Systems using Change-Point Correlations*, 571–575 (doi: 10.1137/1.9781611972757.63)

Idé T and Tsuda K (2007) Change-point detection using Krylov subspace learning. In *Proceedings of the SIAM International Conference on Data Mining*, 515–520 (doi: 10.1137/1.9781611972771.54)

Kolvenbach H and others (2026) Lunarleaper—a mission concept to explore the lunar subsurface with a small-scale legged robot. *Acta Astronautica*, **240**, 63–75, ISSN 0094-5765 (doi: https://doi.org/10.1016/j.actaastro.2025.11.039)

Liu Y, Yuan Z, Li Y and Zhao H (2021) A Three-dimensional path planning method of autonomous burrowing robot for lunar subsurface exploration. In *2021 6th IEEE International Conference on Advanced Robotics and Mechatronics (ICARM)*, 710–715 (doi: 10.1109/ICARM52023.2021.9536059)

McKay CP, Andersen D and Davila A (2017) Antarctic environments as models of planetary habitats: University Valley as a model for modern Mars and Lake Untersee as a model for Enceladus and ancient Mars. *The Polar Journal*, **7**(2), 303–318 (doi: 10.1080/2154896X.2017.1383705)

Moskvina V and Zhigljavsky A (2003) An algorithm based on singular spectrum analysis for change-point detection. *Communications in Statistics-Simulation and Computation*, **32**(2) (doi: 10.1081/SAC-120017494)

NASA Science (2024) To20a astrobotic clps delivery. https://science.nasa.gov/lunar-science/clps-deliveries/to20a-astrobotic/, accessed: 2026-05-19

Osinski GR, Lee P, Spray JG, Parnell J, Lim DSS, Bunch TE, Cockell CS and Glass B (2005) Geological overview and cratering model for the Haughton impact structure, Devon Island, Canadian High Arctic. *Meteoritics & Planetary Science*, **40**(12), 1759–1776 (doi: https://doi.org/10.1111/j.1945-5100.2005.tb00145.x)

Paulsen G, Zacny K, Chu P, Mumm E, Davis K, Frader-Thompson S, Petrich K, Glaser D, Bartlett P, Cannon H and Glass B (2006) Robotic drill systems for planetary exploration. In *Space 2006*, AIAA Conference Proceedings, American Institute of Aeronautics and Astronautics (doi: 10.2514/6.2006-7512), paper AIAA 2006-7512

Paulsen G, Zacny K, McKay C, Shiraishi L, Kriechbaum K, Glass B, Szczesiak M, Santoro C, Craft J, Malla RB and Maksymuk M (2010) *Rotary-Percussive Deep Drill for Planetary Applications*, 1423–1436 (doi: 10.1061/41096(366)128)

Paulsen G, Mank Z, Wang A, Chow P, Hyman C, Thomas T, Lee A, Zacny K, Smith J, Quinn J, Mumm E and Hayes R (2018) The Regolith and Ice Drill for Exploration of New Terrains (TRIDENT); a One-Meter Drill for the Lunar Resource Prospector Mission. *Proceedings of the 44th Aerospace Mechanisms Symposium*

Sheppard A and Skinner KA (2025) Marslgpr: Mars rover localization with ground penetrating radar. *IEEE Transactions on Field Robotics*, **2**, 906–919 (doi: 10.1109/TFR.2025.3628826)

Statham SM (2011) *Autonomous structural health monitoring technique for interplanetary drilling applications using laser doppler velocimeters*. Ph.D. thesis, Georgia Institute of Technology, Atlanta, Georgia

STMD N (2026) 2026 civil space shortfalls

Stoker C, Dunagan S, Stevens T, Amils R, Gómez-Elvira J, Fernández D, Hall J, Lynch K, Cannon H, Zavaleta J, Glass B, and Lemke L (2004) Mars analog rio tinto experiment (marte): 2003 drilling campaign to search for a subsurface biosphere at rio tinto spain. In *35th Lunar and Planetary Science Conference*

Stucky T (2018) Autonomous regolith extraction using real-time diagnostics and dynamic plan execution for 1 meter class interplanetary rotary-percussive drills. In *16th Biennial Int'l Conf. on Engineering, Science, Construction, and Operations in Challenging Environments*, American Society of Civil Engineers (ASCE), Reston, VA

United States Antarctic Program (2000) Antarctic permanent stations. `https://www.usap.gov/USAPgov/sciencesupport/GIS/images/AntarcticPermStations.gif`, accessed: 2026-05-13

Vaquero TS and others (2024) EELS: Autonomous snake-like robot with task and motion planning capabilities for ice world exploration. *Science Robotics*, **9**(88), eadh8332 (doi: 10.1126/scirobotics.adh8332)

Wagner NY, Hahn AS, Andersen D, Wilhelm MB, Morgan-Lang C, Vanderwilt M and Johnson SS (2019) Draft genome sequence from a putative new genus and species in the family methanoregulaceae isolated from the anoxic basin of lake untersee in east antarctica. *Microbiology Resource Announcements*, **8**(18), 10.1128/mra.00271–19 (doi: 10.1128/mra.00271-19)

Weber L and Lenz R (2025) Accelerating singular spectrum transformation for scalable change point detection. *IEEE Access*, **13**, 213556–213577 (doi: 10.1109/ACCESS.2025.3640386)

Wei J, Wang A, Lambert JL, Wettergreen D, Cabrol N, Warren-Rhodes K and Zacny K (2015) Autonomous soil analysis by the Mars Micro-beam Raman Spectrometer (MMRS) on-board a rover in the Atacama desert: a terrestrial test for planetary exploration. *Journal of Raman Spectroscopy*, **46**(10), 810–821 (doi: https://doi.org/10.1002/jrs.4656)

Zacny K and Cooper G (2006) Considerations, constraints and strategies for drilling on mars. *Planetary and Space Science*, **54**(4), 345–356, ISSN 0032-0633 (doi: https://doi.org/10.1016/j.pss.2005.12.003)

Zacny K, Bartlett P, Davis K, Glaser D and Gorevan S (2006) Test Results of Core Drilling in Simulated Ice-Bound Lunar Regolith for the Subsurface Access System of the Construction and Resource Utilization eXplorer (CRUX) Project. In *Earth & Space 2006*, 1–8, American Society of Civil Engineers, League City/Houston, Texas, United States, ISBN 978-0-7844-0830-8 (doi: 10.1061/40830(188)64)

Zacny K, Bar-Cohen Y, Brennan M, Briggs G, Cooper G, Davis K, Dolgin B, Glaser D, Glass B, Gorevan S, Guerrero J, McKay C, Paulsen G, Stanley S and Stoker C (2008) Drilling systems for extraterrestrial subsurface exploration. *Astrobiology*, **8**(3), 665–706 (doi: 10.1089/ast.2007.0179)

Zacny K, Paulsen G and Szczesiak M (2011) Challenges and methods of drilling on the moon and mars. In *2011 Aerospace Conference*, 1–9 (doi: 10.1109/AERO.2011.5747261)

Zacny K, Paulsen G, Kleinhenz J, Smith JT and Quinn J (2017) Development and testing of the lunar resource prospector drill. In *Proceedings of the 48th Lunar and Planetary Science Conference*, Lunar and Planetary Institute

Zacny K, Chu P, Vendiola V, Creekmore P, Ng P, Goldman S, Seto E, Bywaters K, Bailey E, Zheng R, King I, Rashedi A, Chow P, Huddleston R, Paulsen G, Wang A, Wilson J, Quinn J, Eichenbaum A, Captain J, Kleinhenz J, Rezich E, Lim D, Mirmalek Z, Lees D, Elphic R, Smith KE, Colaprete T, Bickel V, Lewis K and Viper Teams T Prime-1 (2024) Development of TRIDENT Drill for Ice Mining on the Moon with NASA PRIME-1 and VIPER Missions. In *Earth and Space 2024*, 280–293, American Society of Civil Engineers, Miami, Florida, ISBN 978-0-7844-8573-6 (doi: 10.1061/9780784485736.026)

Zacny K, Chu P, Vendiola V, Paulsen G, Creekmore P, Goldman S, Bailey J, Ng P, Fortuin C, Stamboltsian J, Wang A, Jain A, Chow P, Seto E, Bottomley N, Huddleston R, Bailey-Kelly E, Zheng R, Norlinger A, King I, Mank Z, Wilson J, Fishman J, Xu H, Bergman D, Mumm E, Davis K, Beck J, Dearing S, Hill M, Quinn J, Eichenbaum

A, Captain J, Kleinhenz J, Colaprete A, Elphic R, Ennico-Smith K, Lim DSS, Mirmalek Z, Lees D, Bickel VT, Deutsch AN, Schmerr NC, Lewis K, Fernando B and Gansler K (2025) Trident ice mining drill for lunar volatile prospecting for prime-1 and viper missions. *The Planetary Science Journal*, **6**(297) (doi: 10.3847/PSJ/ae0b51)