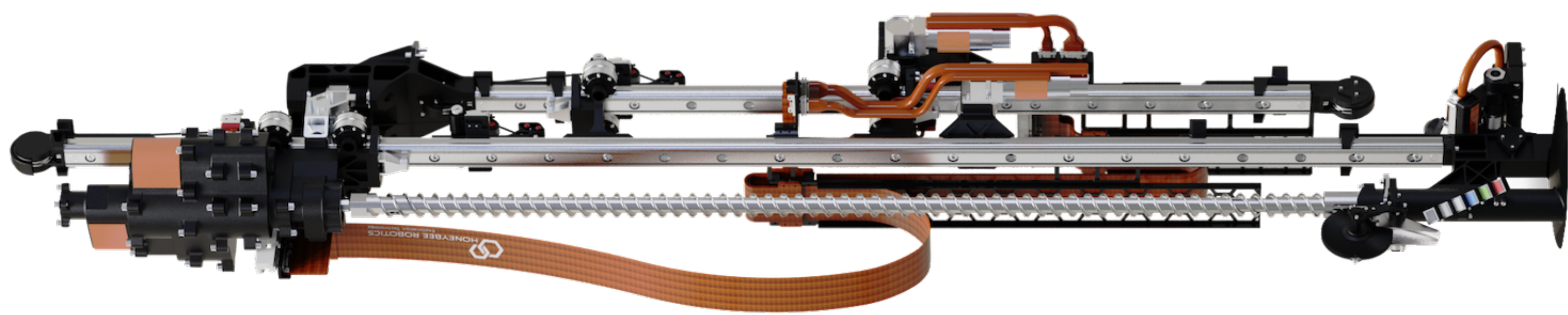


Towards Planetary Drilling Autonomy using Subsurface Fault and Anomaly Detection

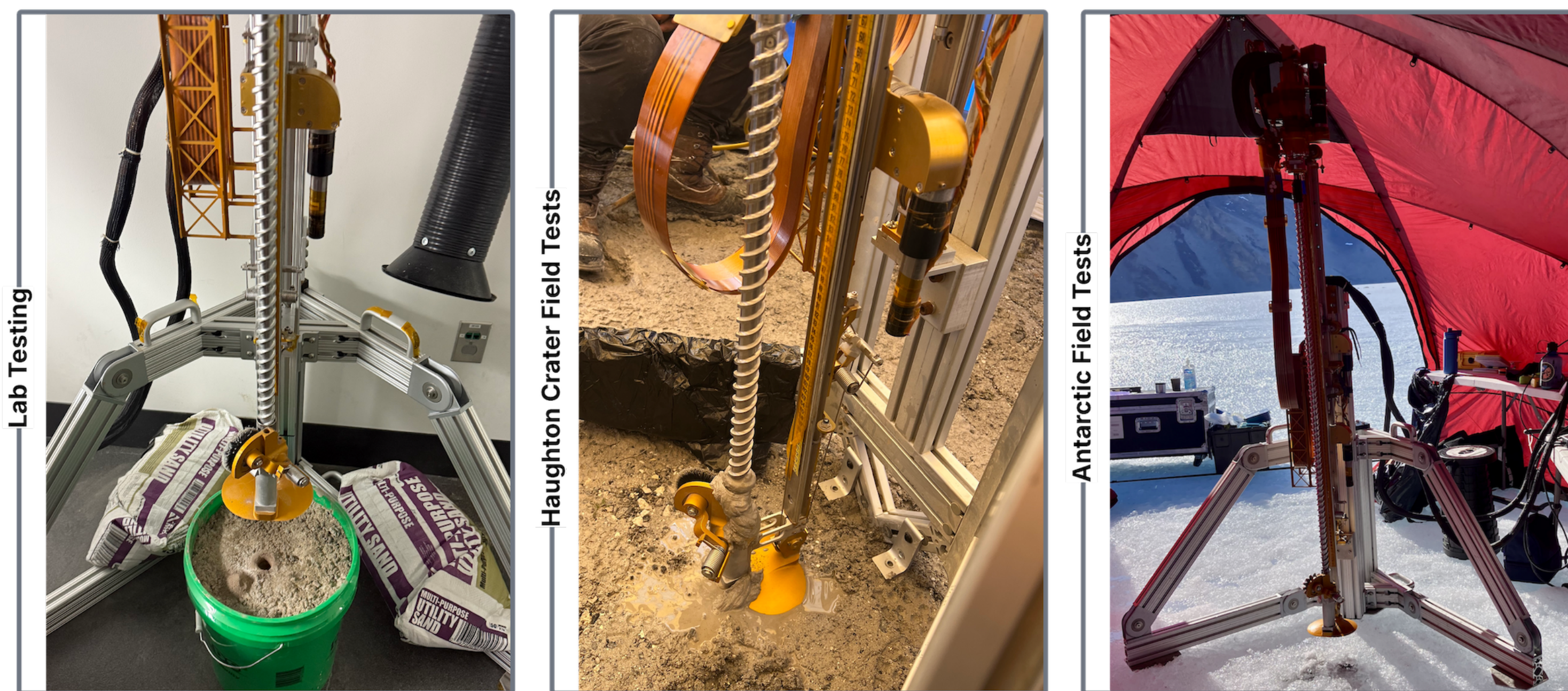
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Abstract

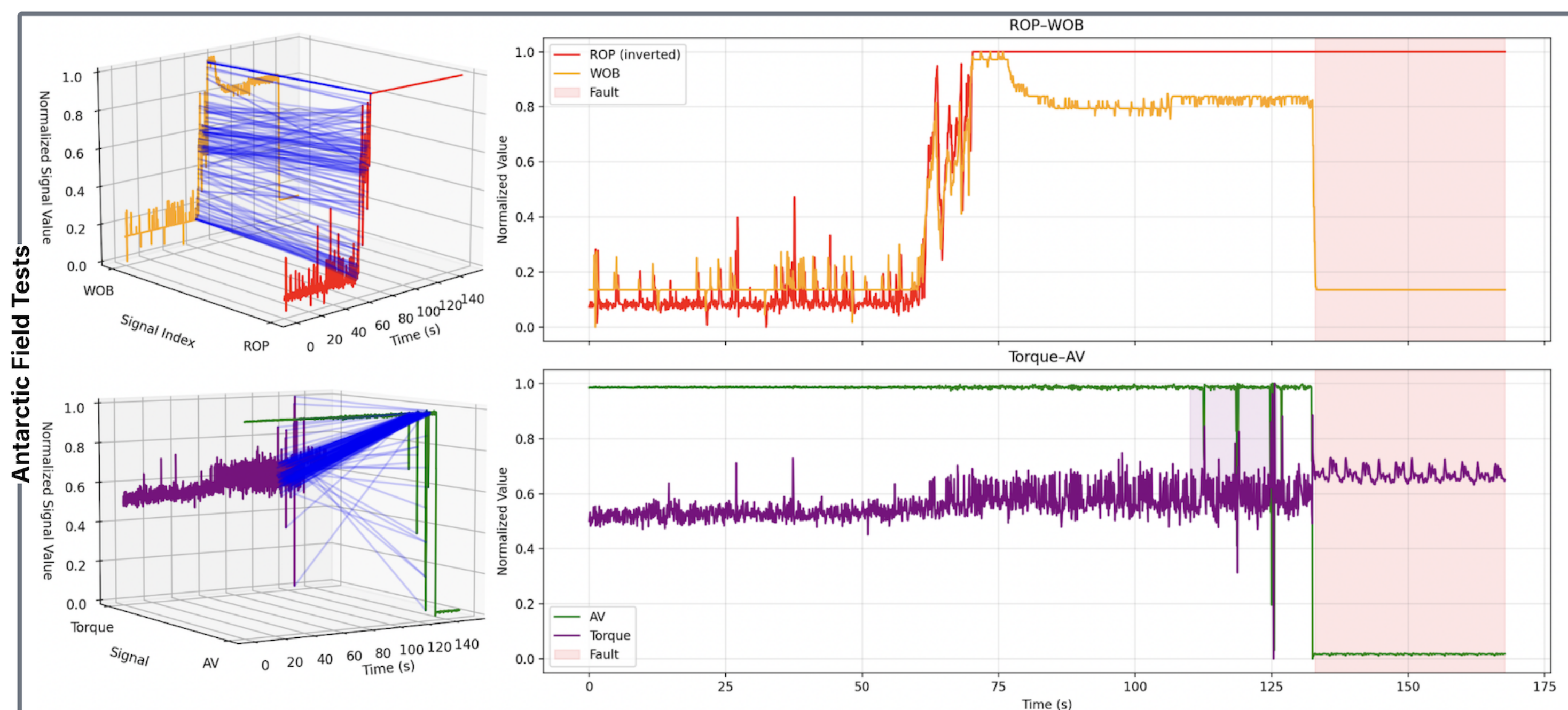
In extraterrestrial planetary environments, environmental, computing, energy, and operational constraints require robotic agents to complete tasks without human supervision. Specialized extraterrestrial robotic drilling agents currently lack autonomous drilling capabilities, primarily because research into subsurface environment for autonomous drilling remains in its early stages. We validate work using online model-free time-series subspace analysis method, Enhanced Singular Spectrum Transformation, (ESST) [1], for noisy and sparse data to estimate drilling faults from drill avionics telemetry in Houghton Crater in the Canadian High Arctic. We introduce a multivariate subsurface anomaly detection method, Multivariate Enhanced Singular Spectrum Transformation (MESST), that leverages sensor fusion of avionics telemetry evaluated at Mars planetary analog sites in Antarctica. We also outline planned fieldwork in summer 2026 at Barringer Crater.



Left: lab testing using regolith simulant buckets designed to quickly induce faults. Middle: drilling up to 1 m at Houghton Crater field site, validating ESST fault and anomaly detection software in an environment mimicking Mars conditions. Right: drilling up to 1 m at Lake Untersee, Antarctica, evaluating MESST Sensor Fusion in another planetary analog.

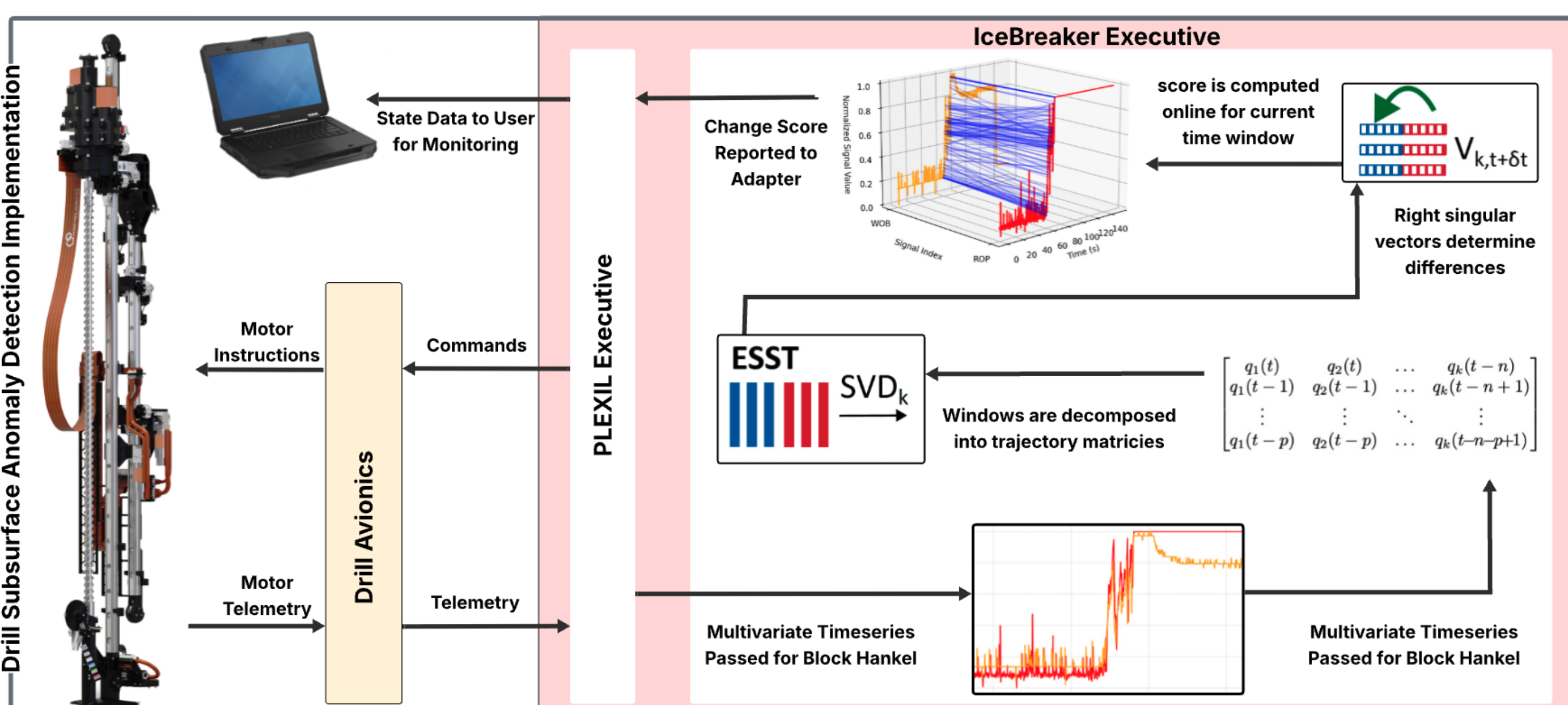
Introduction

Faults tend to raise variables like motor torque τ , weight on bit ϕ , while the rate of penetration ρ is roughly zero. The Auger Velocity ω of the drill string tends to have sudden dips from getting caught or stuck briefly with increased friction in the borehole leading up to a fault.[2].



Top graph is inverted rate of penetration ϕ and weight on bit ρ telemetry streams. Bottom graph is torque τ and auger velocity ω telemetry streams. The left graphs illustrate how similar changes in complimentary fault telemetry could be used for sensor fusion.

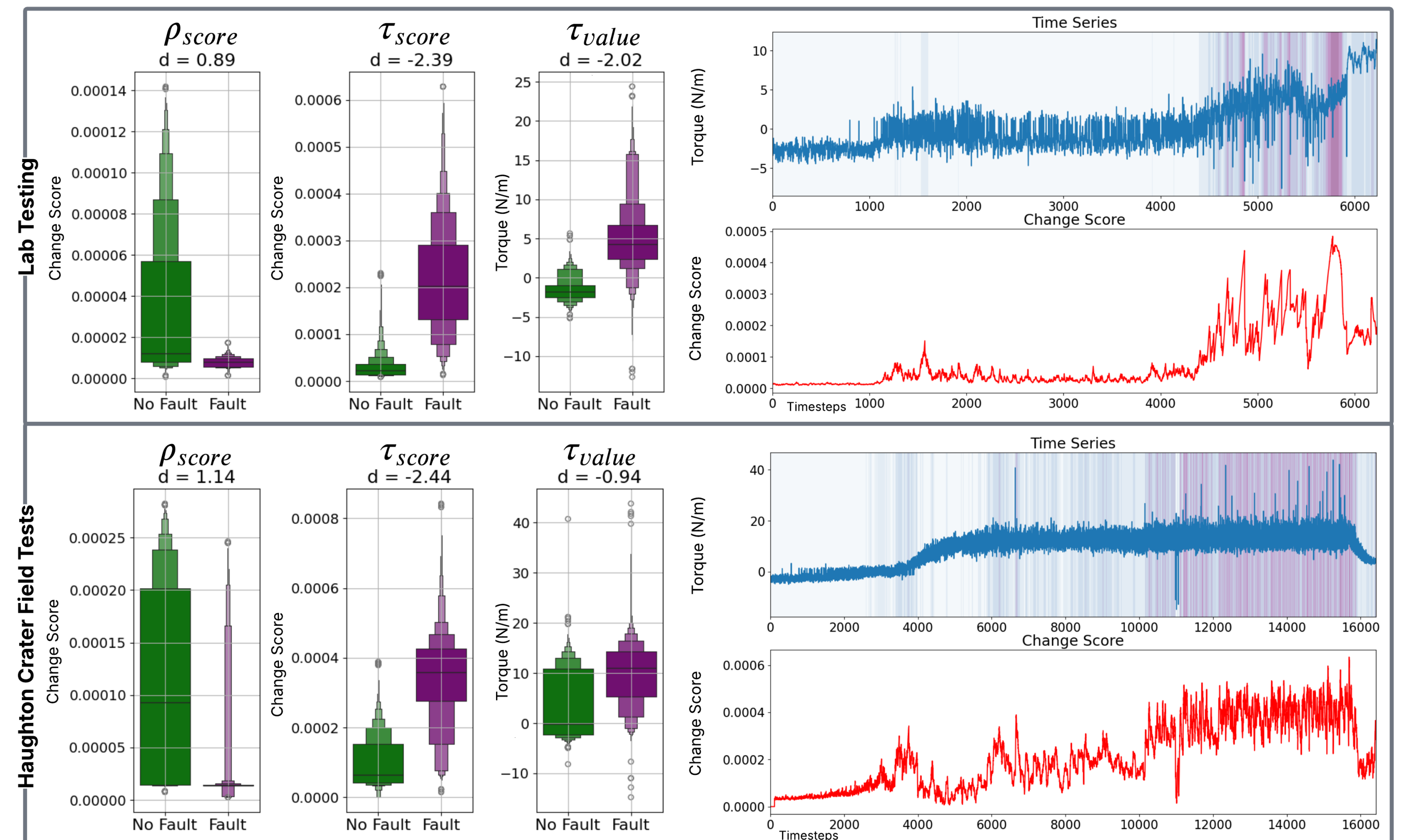
Implementation on TRIDENT Drill



Univariate and Multivariate Subsurface Anomaly Detection Implementation. Motor Telemetry comes into the drill avionics. It is fed to the PLEXIL executive at a rate of 40Hz, and passes windows of data to our ESST/MESST Module. The data windows are then decomposed into block Hankel matrices, and the right singular vectors determine any significant changes, which are then used to compute the multivariate score. The change score is then passed to the user.

Results

Results reinforce prior findings [2] that ESST online telemetry monitoring improves anomaly and fault detection despite limited data. For the Houghton Crater evaluation, results from ρ score, τ score, and τ telemetry indicate effective subsurface anomaly and fault detection.



Top graphs shows results from lab testing and bottom set shows results from Field testing. Left graphs in top and bottom show score distributions and Cohen's D score showing the difference between faulty and non-faulty datasets. Right top and bottom plots show motor torque τ time series data over a fault with the corresponding online change score. The top right was induced in the lab. Bottom right was a fault encountered at Houghton Crater Analog site. The purple shading indicates severity of the change score, with severity increasing with the buildup to the fault.

Value	Dataset	Cohen's D Value
Location	Lab	Field Site
τ value	-2.02	-0.94
τ score	-2.39	-2.44
ρ score	0.89	1.14

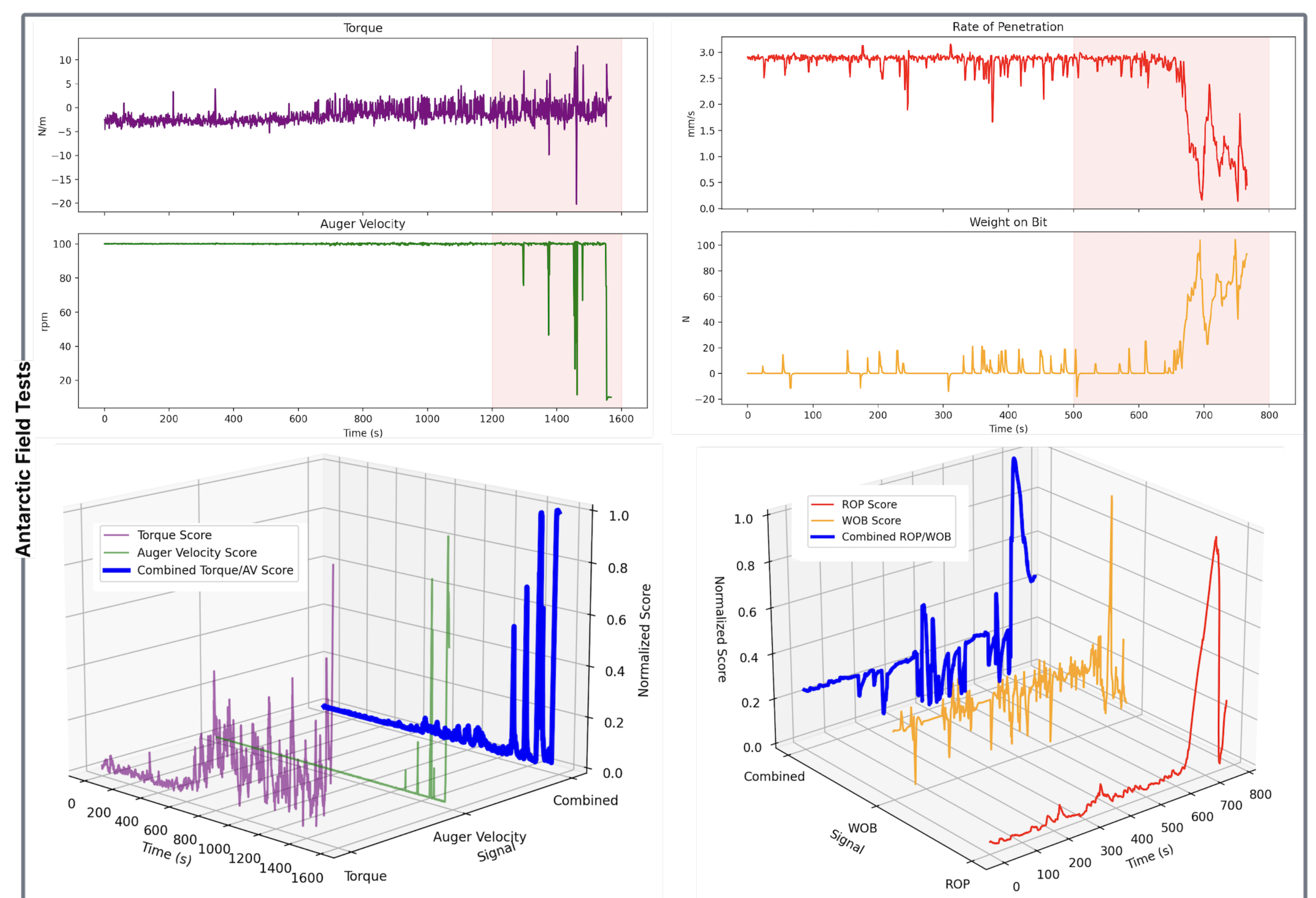
Value	Average F1 Score	
Location	Lab	Field Site
τ score	0.82	0.75
ρ score	0.68	0.78

Signal	$\sigma^2(\sigma_n)$	$\sigma^2(\sigma_f)$
$S_{\tau, \omega}$	0.001378838	0.082164826
S_{τ}	0.006287162	0.046934778
S_{ω}	0.000000009	0.024155776
$S_{\rho, \phi}$	0.026078975	0.050281532
S_{ρ}	0.027251228	0.065119327
S_{ϕ}	0.019044157	0.025253024

SMD Cohen's D Value and F1 Scores for ESST results. All of our datasets had a Cohen's D score greater than ± 0.8 , indicating faulty telemetry data for our datasets had a significant difference from our non-faulty telemetry data, reflecting lab results. All of our datasets scored F-1 Score above 0.6, indicating good true positive recall.

Weighted average variance for sensor fused MESST scores nominal fault-free (σ_n) and faulty (σ_f) segments. Lower variance in nominal sensor fused segments and higher variance in fault-preceding sensor fused segments show lower noise in nominal segments with higher fault detection accuracy.

MESST performed well in the field, reducing noise in $S_{\tau, \omega}$ and improving fault detection, while also lowering noise in $S_{\rho, \phi}$ without degrading performance.



Left set of graphs shows torque τ , auger velocity ω signals and right set of graphs shows rate of penetration ρ and weight on bit ϕ . Bottom set of graphs show respective individual ESST change scores and fused MESST scores for respective telemetry signals.

Fieldwork in Summer 2026 will take place at Barringer Crater outside of Flagstaff, Arizona. It is frequently used as a planetary analog due its relatively young age at 50,000 years and relatively well-preserved impact crater. During this field exercise, we will evaluate and test autonomous drilling methods currently being prototyped. These methods utilize ESST and MESST for perception of the subsurface environment, in conjunction with other instruments for both surface and subsurface perception.

References

- S. Boelter, G. Brown, L. Weber, T. Stucky, B. Glass, and M. Gini, "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)*, 2026.
- S. Boelter, L. Weber, R. Lenz, B. Glass, and M. Gini, "Fault prediction in drilling using subspace analysis techniques," *Intelligent Autonomous Systems 19, Proc. 19th Int'l Conf IAS-19*, 2025.