LISTER PNEUMATIC EXCAVATION AT MARE CRISIUM

PRELIMINARY DRILLING REPORT FROM BLUE GHOST

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LSITP Objectives and LISTER Approach

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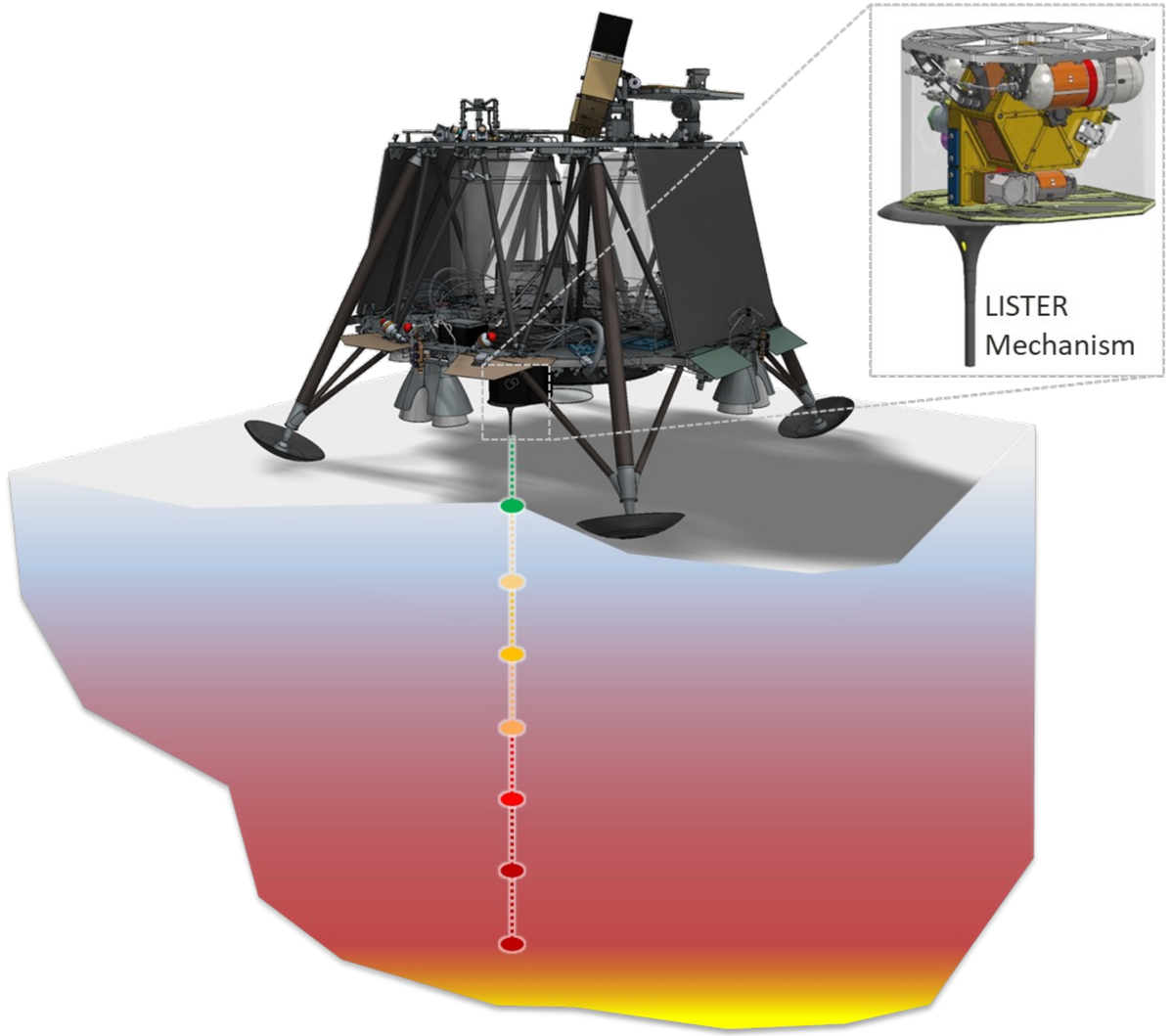
LISTER's goal is to characterize heat flow from the interior of the Moon in support of the following:

Science Mission Directorate (SMD)
Better understand thermal evolution and differentiation history of the Moon

Human Exploration and Operations Mission Directorate (HEOMD) Strategic Knowledge Gaps (SKGs)
Understand lunar resource potential and how to work and live on the lunar surface

Space Technology Mission Directorate (STMD)
Enhance capabilities for future science and exploration missions and commercial Moon development

In support of these goals, **LISTER's objective is to measure the thermal gradient and conductivity of the lunar subsurface penetrated by its drilling probe tip.**



LISTER as Drilling Tech Demonstration

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LISTER's low-mass and low-volume drilling system can **drill holes** and **produce regolith samples** from known depths for science, exploration, and commercial missions.

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Deployment Subsystem Overview

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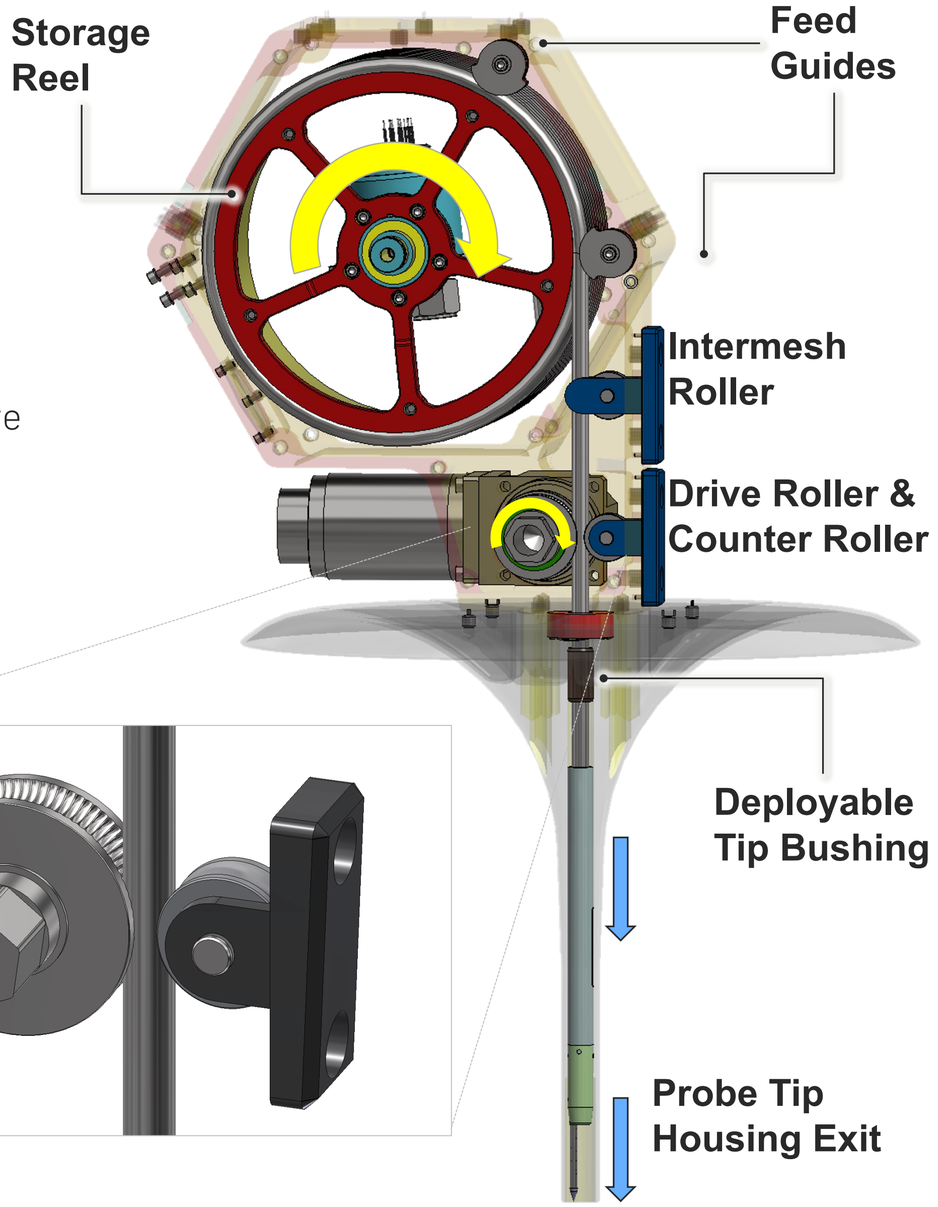
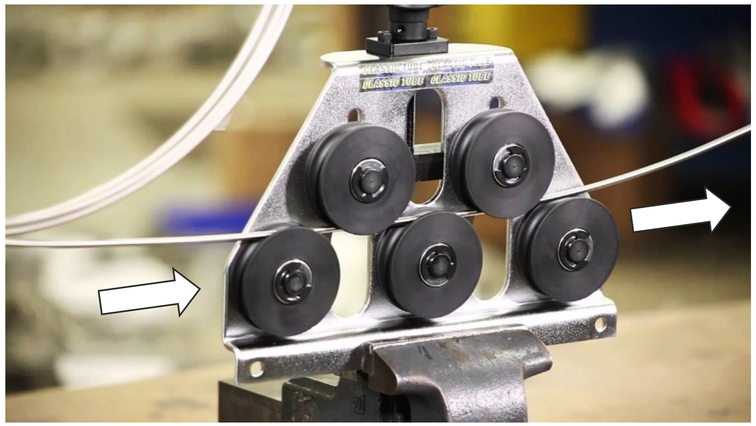
Based on COTS and industrial roller straightener designs

Coiled tubing is plastically yielded to deploy in straight form

1. **Coiled Tubing** is stored on Storage Reel
2. **Drive Roller and Drive Counter Roller** engage Coiled Tubing
3. **Actuator** rotates Drive Roller to pull Coiled Tubing
4. **Intermesh (Straightener) Roller** forms 3-roller straightener with Storage Reel and Drive Roller to straighten tubing
5. **Feed Guides** align Coiled Tubing to fixed deployment plane
6. **Deployable Tip Bushing** provides necessary final boundary condition for controlling straightness



COTS Tubing Straightener



BLUE ORIGIN

Pneumatics Subsystem Overview

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- HIGH-TRL COTS COMPONENTS AND CUSTOM MANIFOLD; ETU BUILT AND TESTED
- STORES N_2 GAS AT 5000 PSIA MEOP DESIGN PRESSURE
- DELIVERS GAS THROUGH STORAGE REEL GAS SWIVEL AND SPINDLE INTERFACE TO COILED TUBING

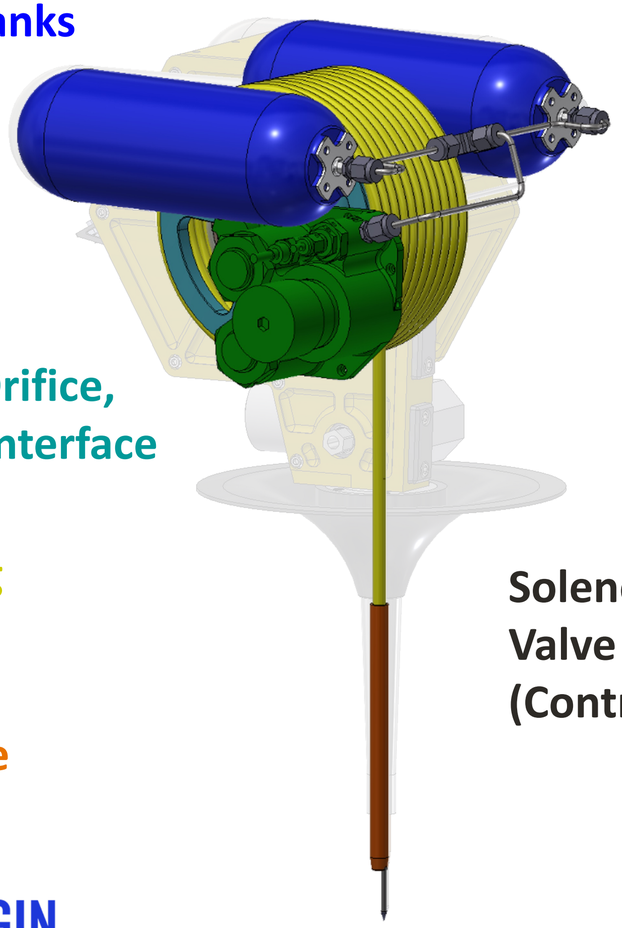
Gas Supply Tanks
GN_2 5000 psi

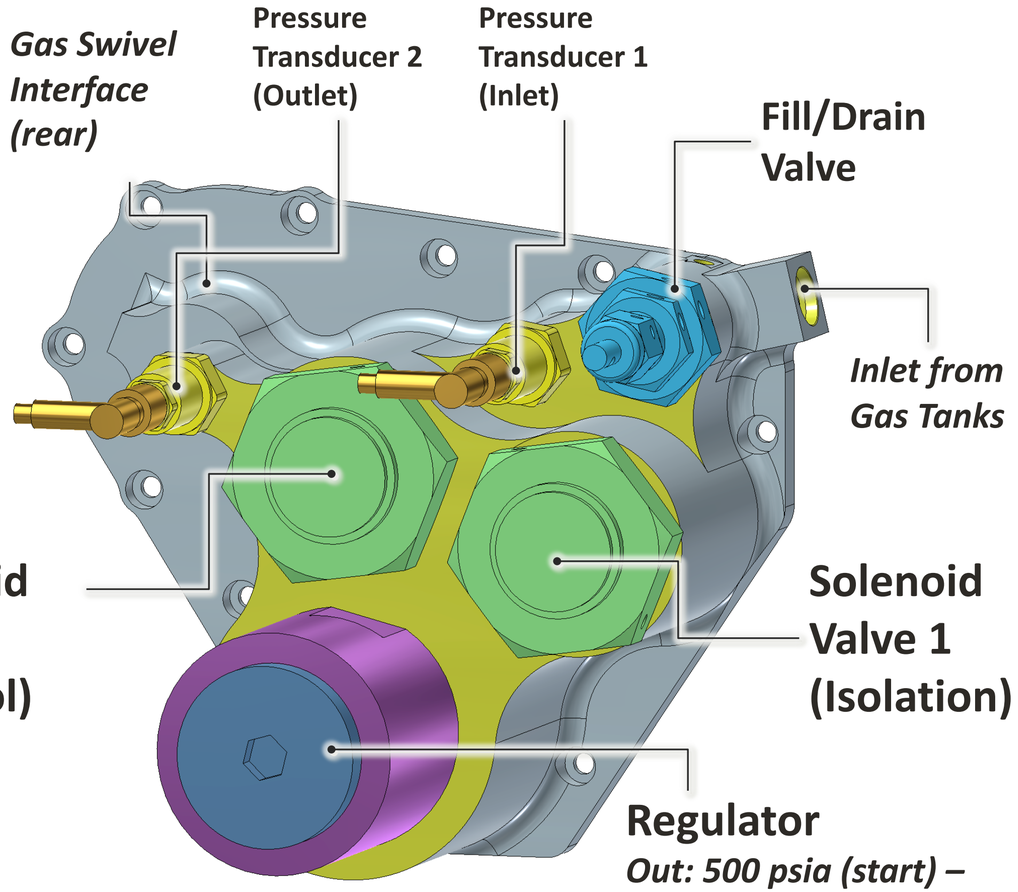
Pneumatics Manifold

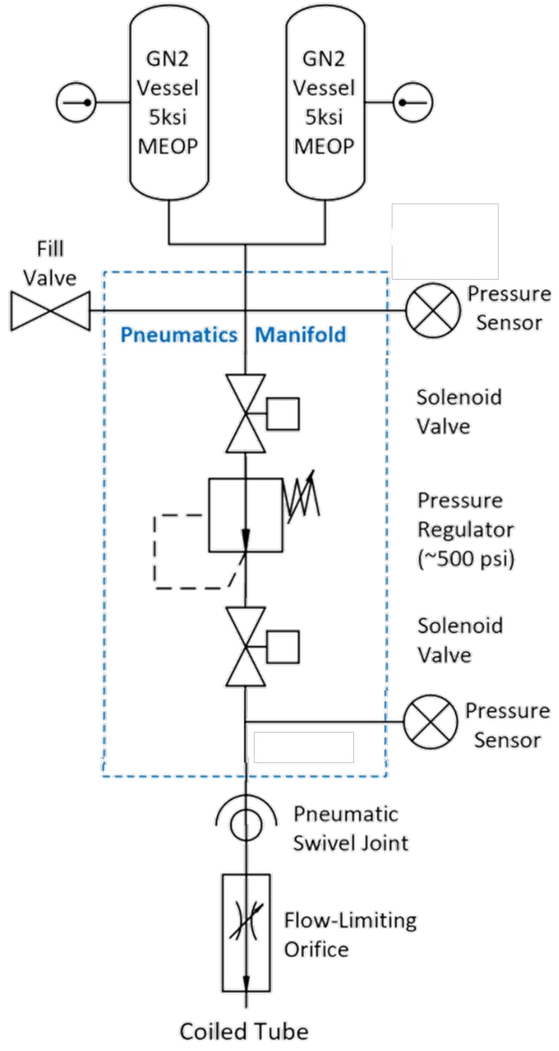
Gas Swivel, Orifice, and Spindle Interface

Coiled Tubing

Spacer Nozzle





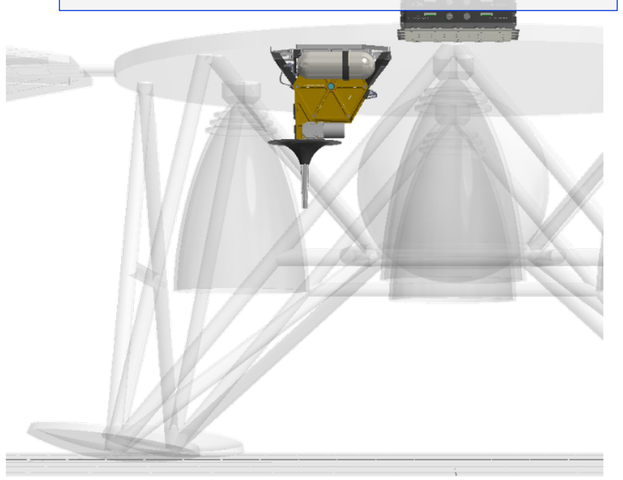


BLUE ORIGIN

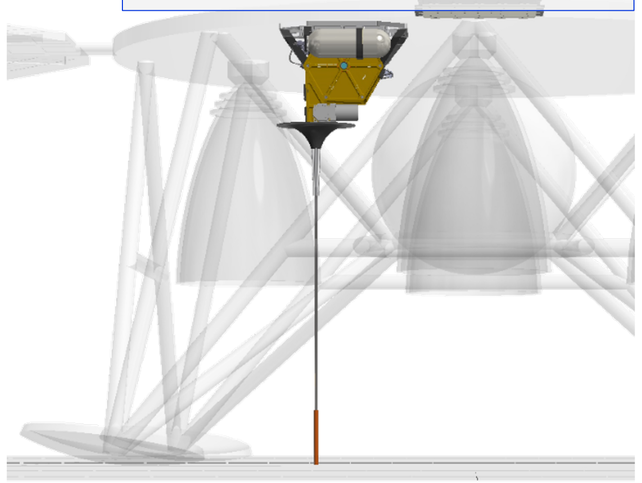
LISTER Con-Ops

- LISTER is a Semi-Autonomous drilling system
  - Earth command sets target depth as well as safeties for early exits of the operation prior to reaching target depth
- Data is received on Earth and processed to decide how to approach the next bite
- LISTER seeks surface, buries the spacer nozzle to take first subsurface measurement, and then moves in commanded bites of up to 500mm

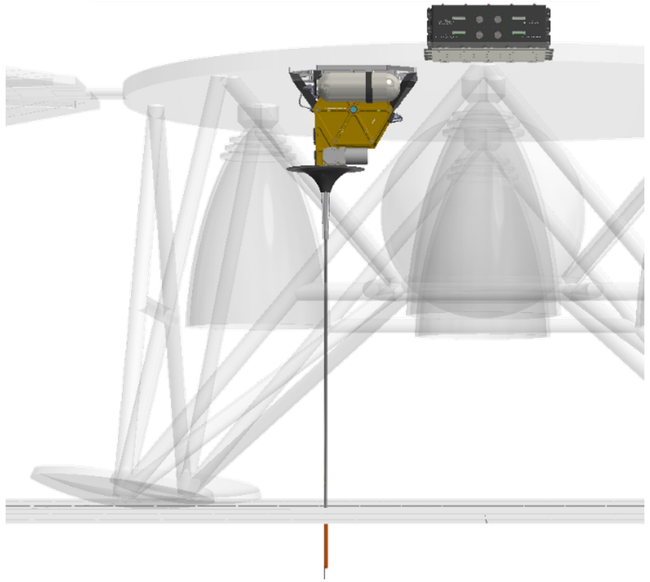
1. Land on Surface



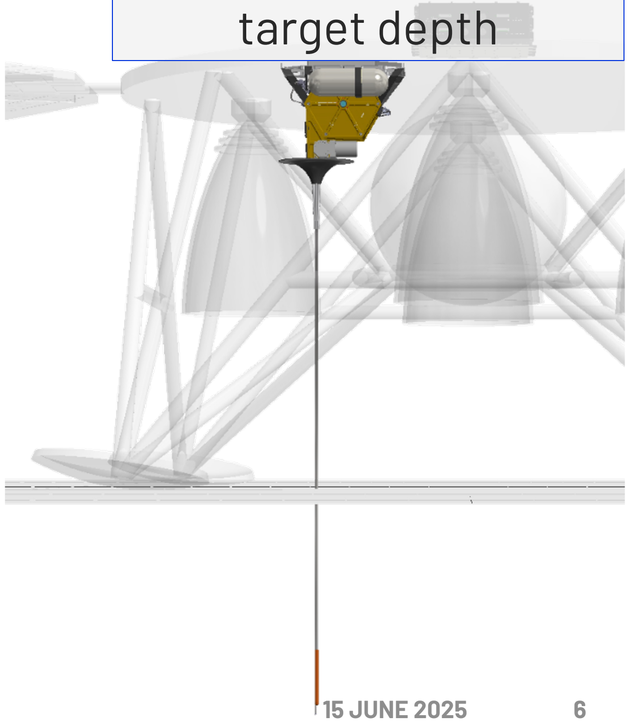
2. Drill Seeks Surface



3. 250mm bite



4 – N. Command new target depth



Rock Hazard Mitigation using “Dithering”

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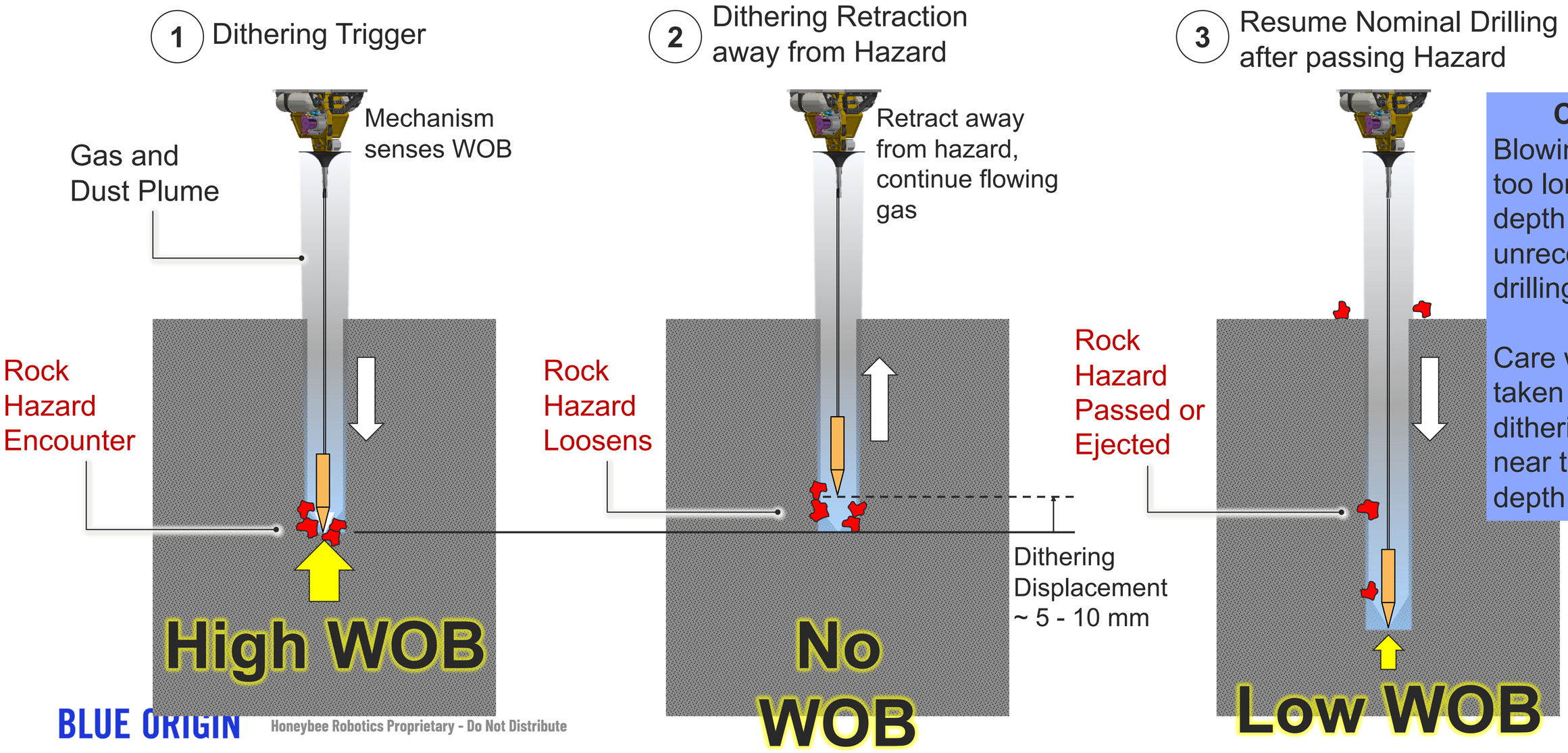
Dithering has proven effective against bridging and buildup of rocks in the borehole bottom



Caution

Blowing gas for too long at one depth can lead to unrecoverable drilling failures

Care will be taken to limit dithering cycles near the same depth

Project Background – Landing Site Selection

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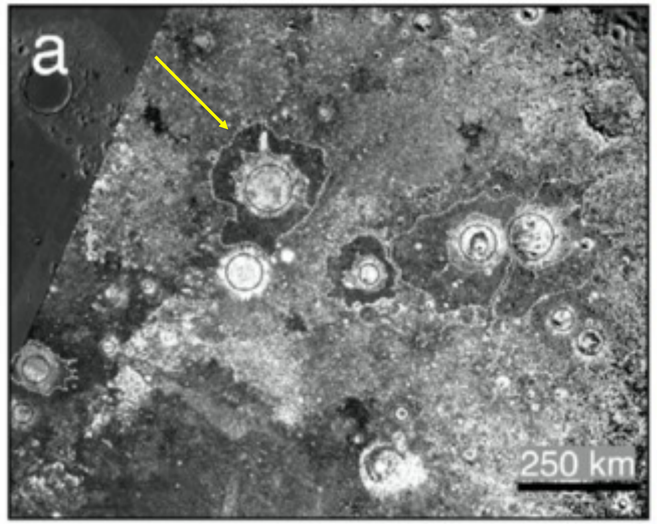
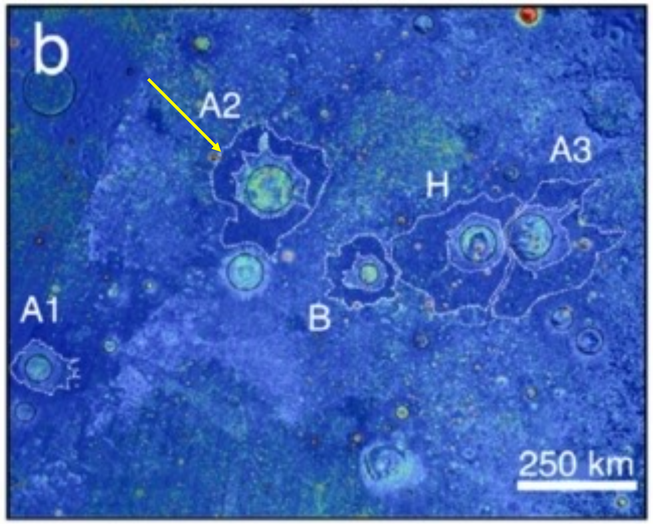
Rock Abundance analysis:
LRO-Diviner and Arecibo Radar data were used to identify areas of low rock concentration from the surface down to ~7-m depth

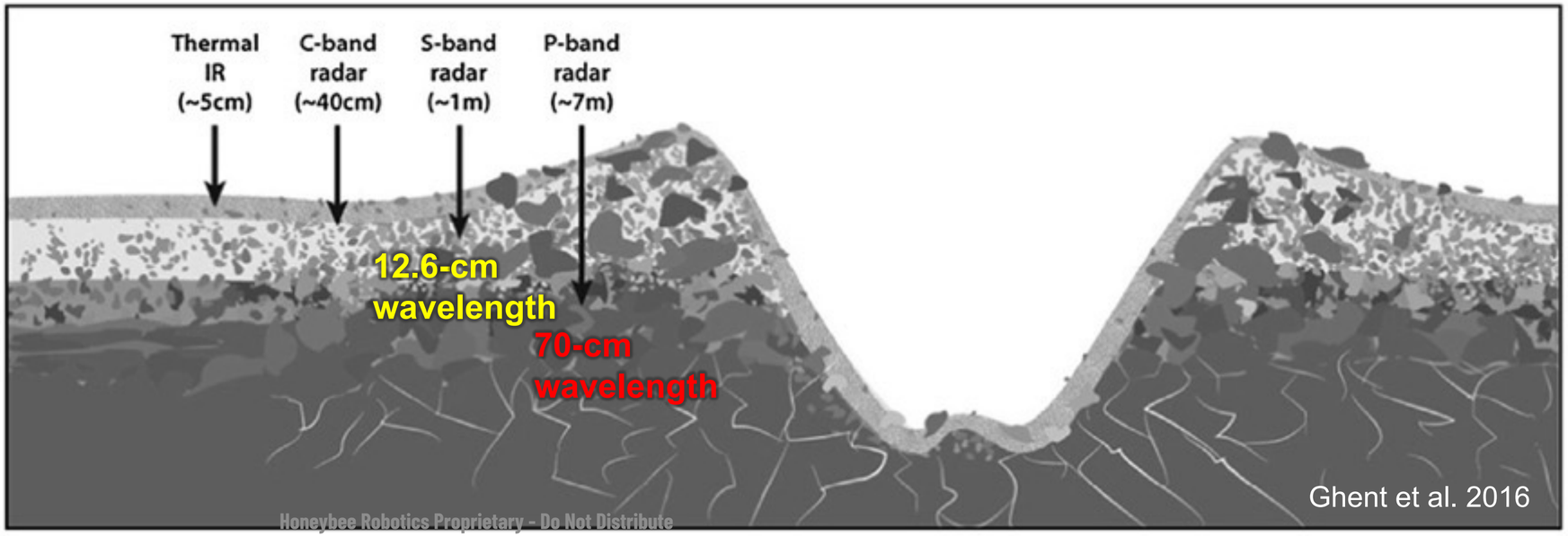
Examples:

Arecibo P-band CPR



LRO-Diviner Rock Abundance





Ghent et al. 2016

LISTER Ops – First Operation

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Video Courtesy Firefly Aerospace

Drilling at the Near Surface

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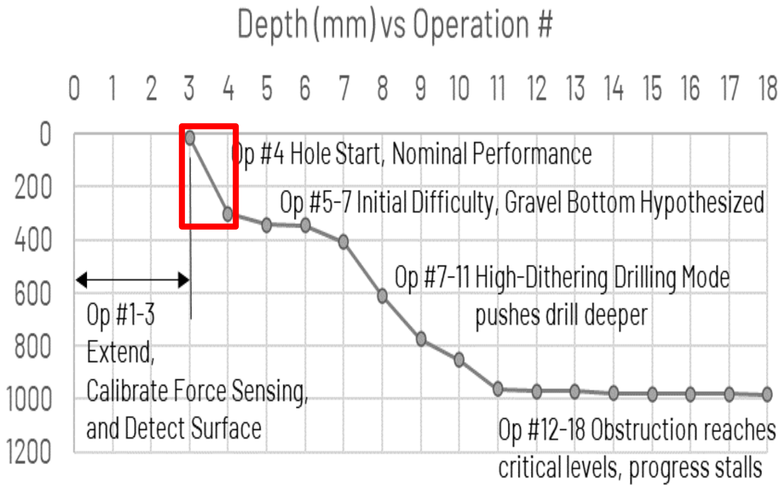


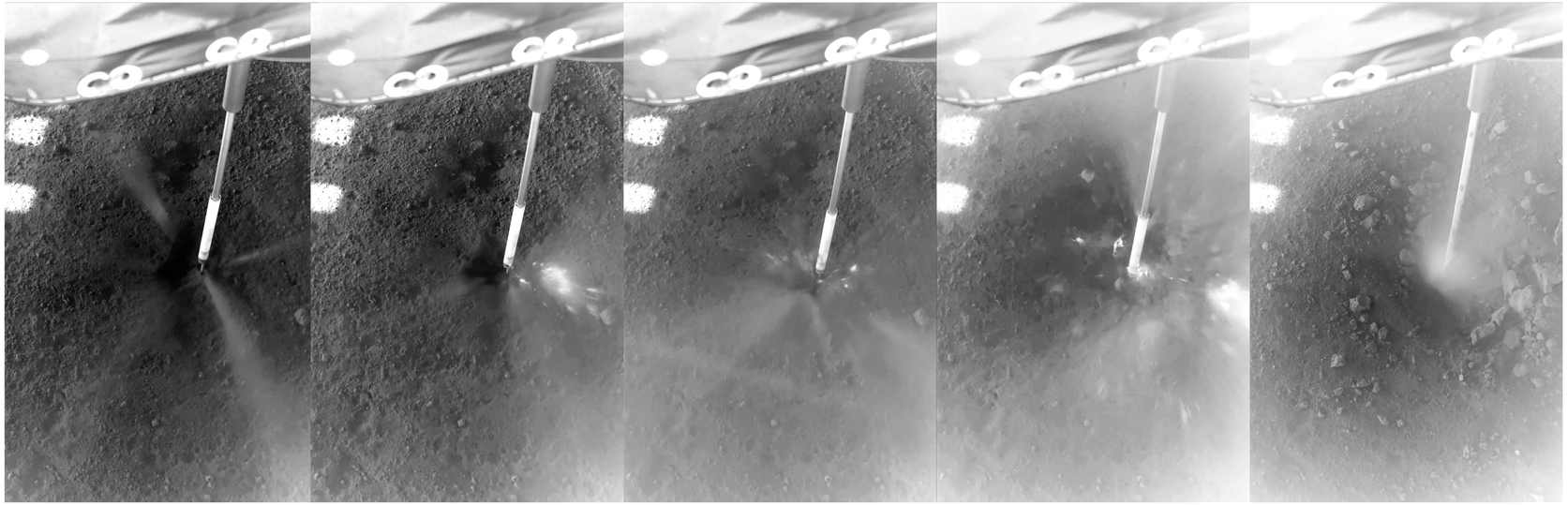
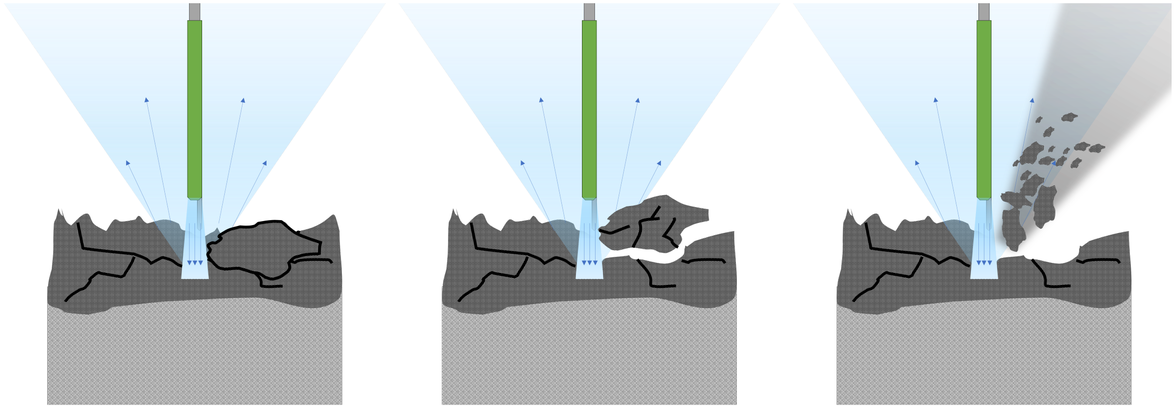


Photo Courtesy Firefly Aerospace

- Highly compacted regolith at surface or in layers fractures into “eruption” of clumps of regolith
- Target depth of 250mm achieved, nominal performance

Hypothesized Rapid Ablation Cascade

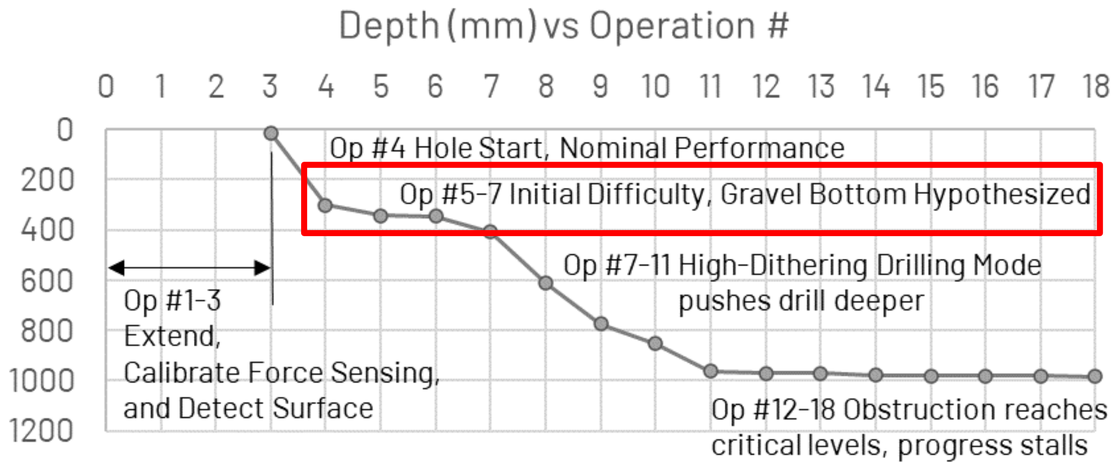


1 - Initial “fractures” develop as gas jet pressure disrupts consolidated crust

2 - Consolidated regolith clod separates and becomes lofted, developing new fractures

3 - New fractures cascade and clod rapidly disintegrates, leading to explosive ablation “eruption”

First Obstacles



- As seen in developmental testing, when there is a layer or high concentration of “gravel” (>1mm sized pebbles) , a “gravel bottom” condition can form
- Fines are excavated but gravel is not, leaving a bulb in the bottom hole

Photo from LISTER Developmental Testing

Progress Through Changed Operational Parameters

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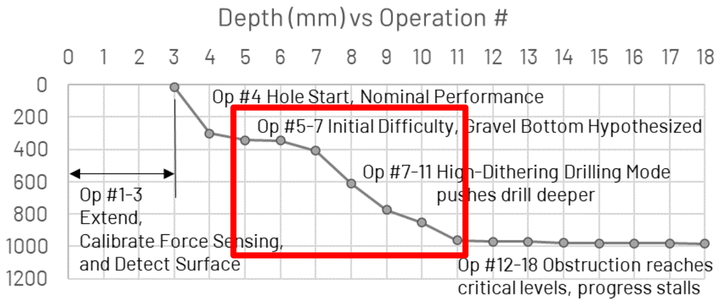
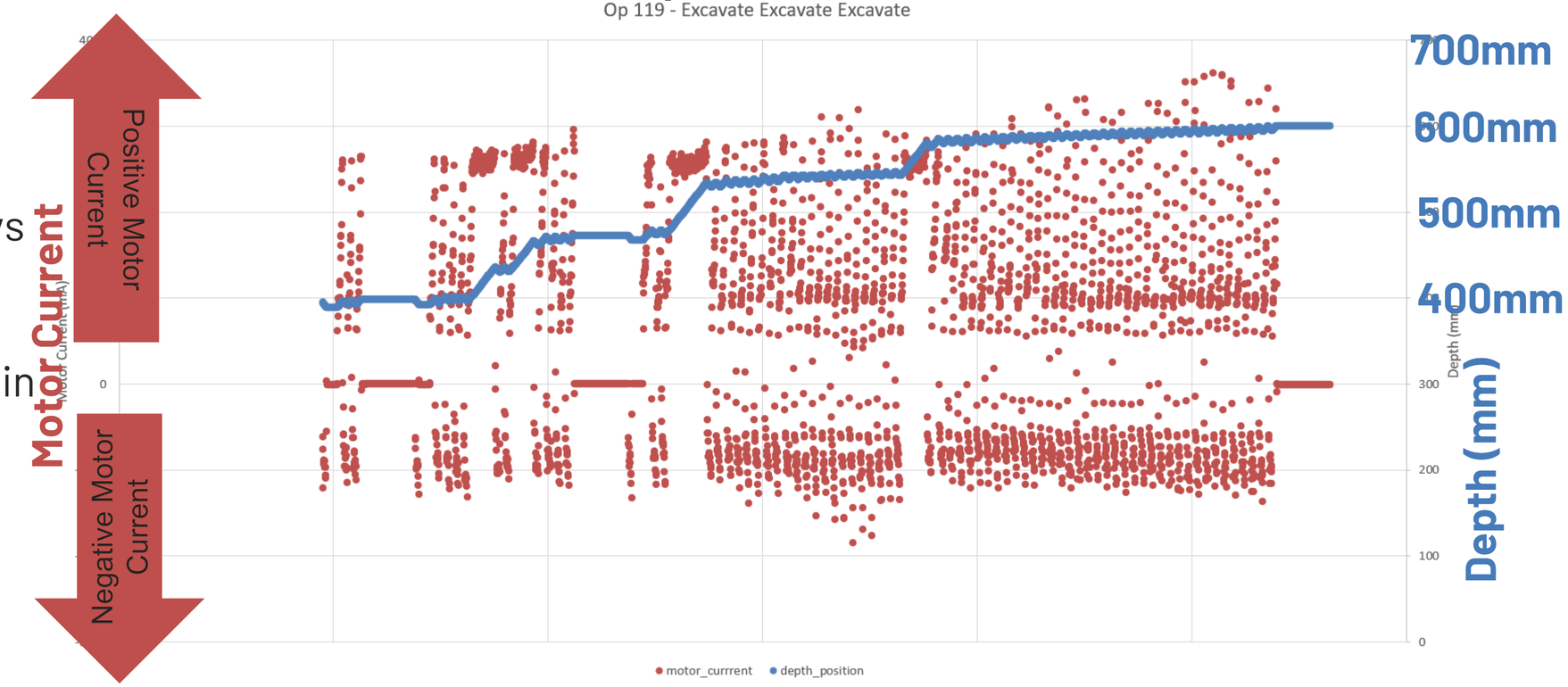
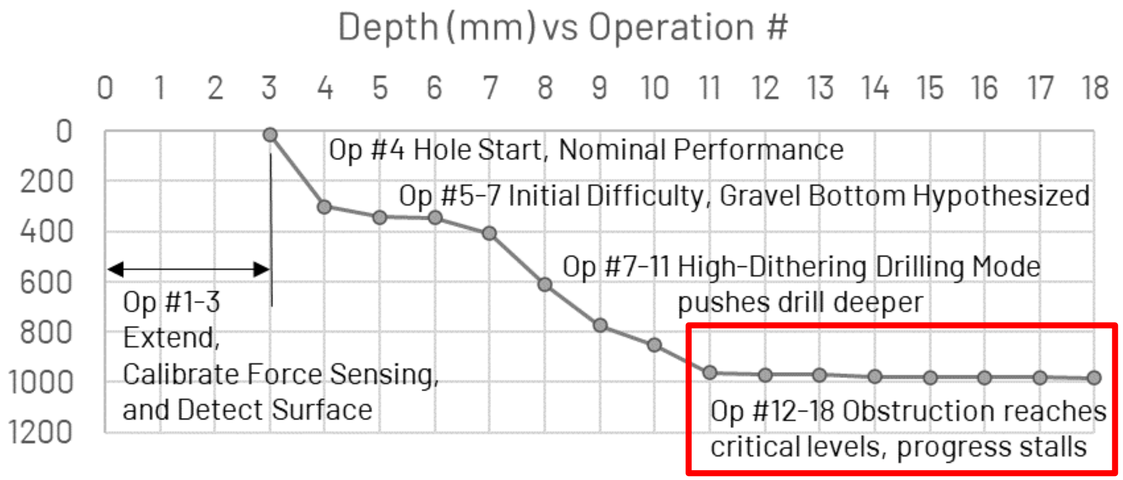


- Reduced dither retract distance vs nominal, leading to a “pecking” behavior of drill
  - Increased number of dithers in one spot prior to exit
- Prolonged “pecking” in one spot before making significant jump in progress
- Video was unable to be captured during these drilling events



Drilling End of Life



- Eventually, enough gravel had settled at the bottom of the hole that LISTER could not progress without running into motor stalling issues, signaling end of life for drilling progression
  - Science measurements at bottom hole continued into the beginning of lunar night
- Despite realizing risks associated with limiting total drilling depth, LISTER became the first robotic measurement of lunar heat flow and the deepest-reaching robotic planetary subsurface thermal probe

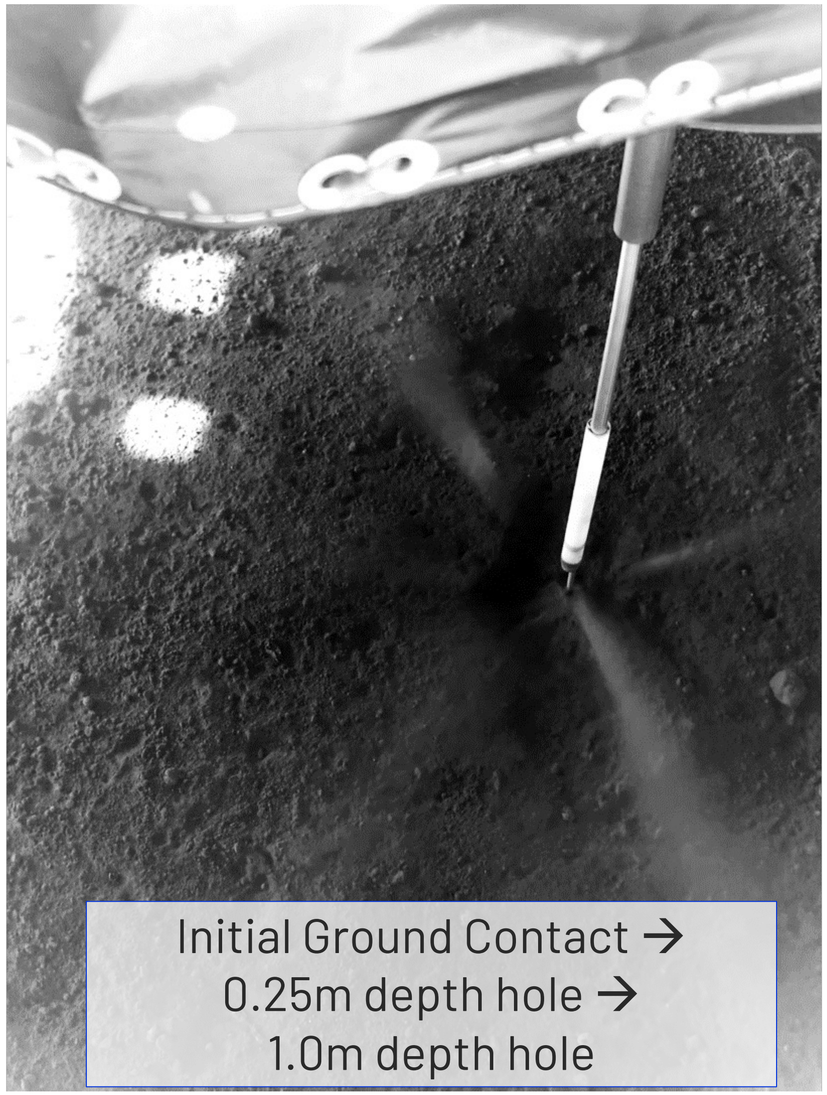


Photo Courtesy Firefly Aerospace

QUESTIONS?