PRIME-1
Polar Resources Ice Mining Experiment-1

NASA's First Polar Drilling and Volatiles Detection Mission on the Moon

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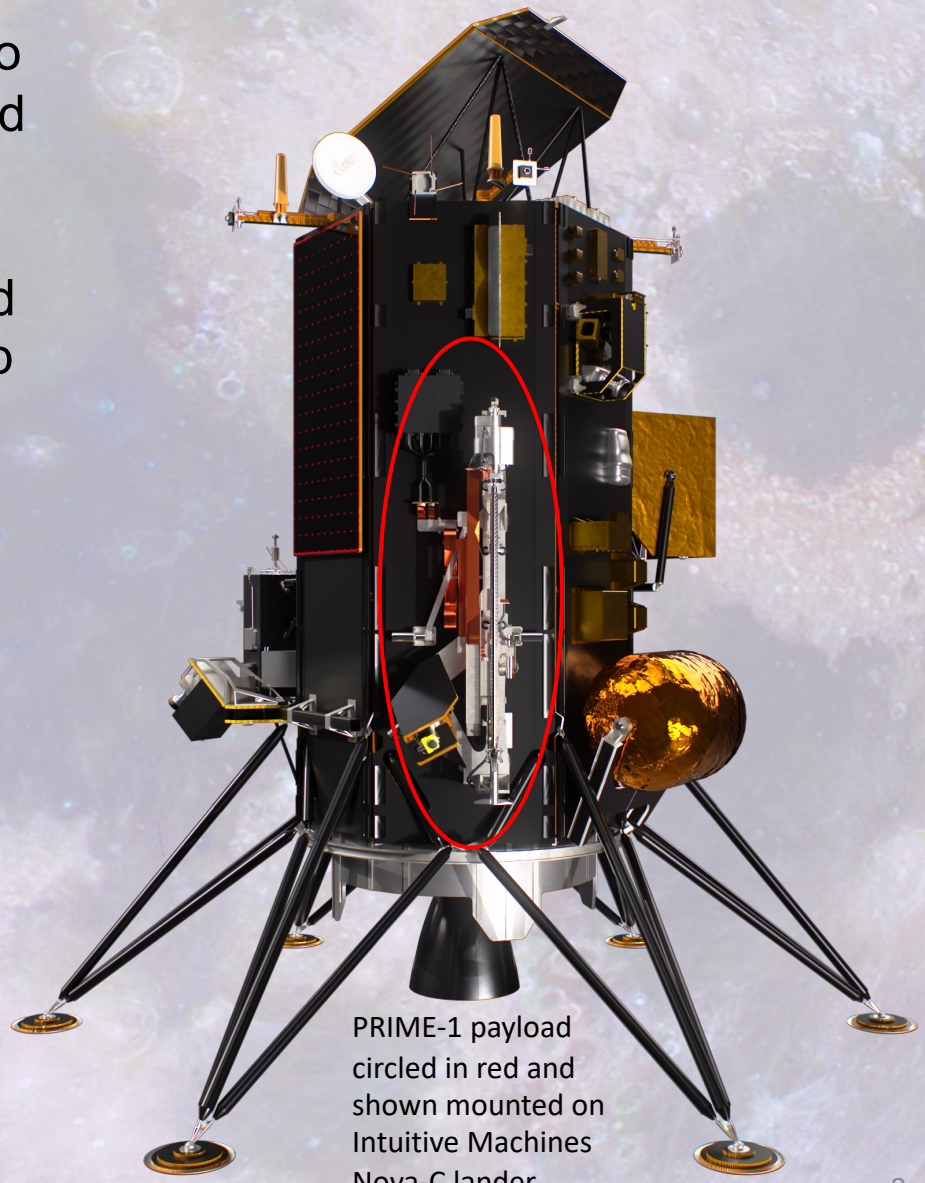
Overview

- NASA is leveraging novel public/private partnerships with industry to meet the Agency's objective to return to the surface of the Moon and develop a sustainable lunar ecosystem
- NASA's initial approach to fulfill this goal is to fly payloads that could be ready to land on the Moon early this decade, some of which help inform ISRU objectives
- PRIME-1 is a Space Technology Mission Directorate ISRU payload
- The instruments that make up PRIME-1 are:
  - MSolo (Mass Spectrometer observing lunar operations)
  - TRIDENT (The Regolith Ice Drill Exploring New Terrain)
- PRIME-1 will attempt to acquire a direct measurement of polar volatiles, informing our understanding of the lateral and vertical distribution of the volatiles at the landing location down to a meter deep from Intuitive Machine's Nova-C lander



PRIME-1 payload circled in red and shown mounted on Intuitive Machines Nova-C lander

Partnerships & Mission Infusion

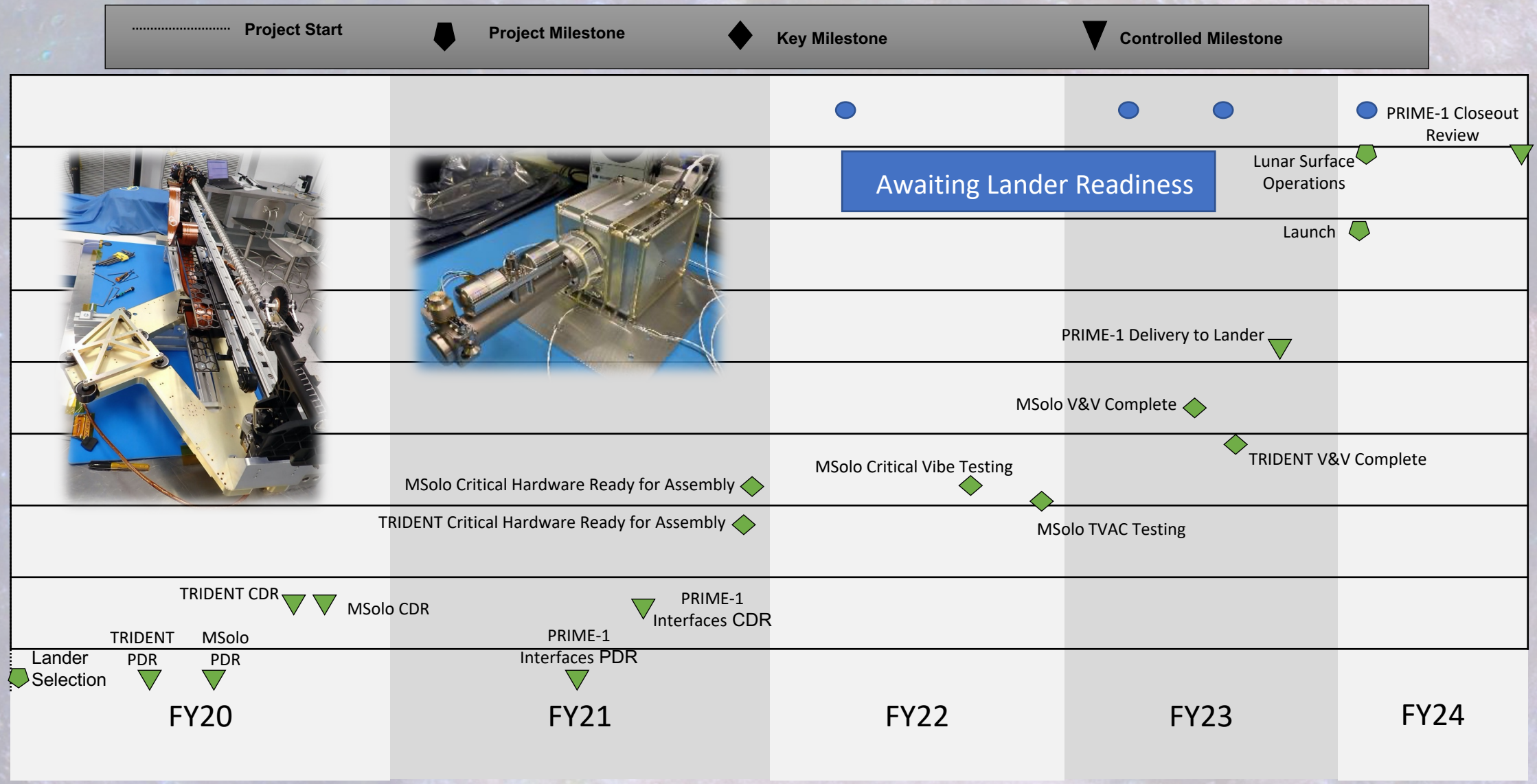
- Contributing partners and/or stakeholders
  - Space Technology Mission Directorate-Game Changing Division
  - Honeybee Robotics – TRIDENT drill commercial partner (CA and CO offices)
  - INFICON – MSolo mass spectrometer commercial partner (NY)
  - Blue Sun – SBIR Phase III Virtual Machine Language (CO)
  - National Science Foundation (NSF) – SHREC (Space, High-performance, and Resilient Computing) Space Processor design
  - SMD –Commercial Lunar Payload Services (CLPS) carrier contract and Science modeling (two SSERVI nodes participating)
- Mission Infusion
  - PRIME-1 is currently targeting a late CY 2023 CLPS mission to Shackleton's connecting ridge at the lunar south pole; carried by Intuitive Machines
  - PRIME-1 will help to inform the Agency plan for ISRU prospecting at the lunar poles
  - PRIME-1 will inform VIPER mission ops
  - Any data acquired from the operation of PRIME-1 will be uploaded to the Planetary Data System for use by the lunar science community and the ISRU community

MSolo on vibration test fixture

TRIDENT mounted on Intuitive Machines' 3PO Pallet


PRIME-1
MSolo

Development Timeline

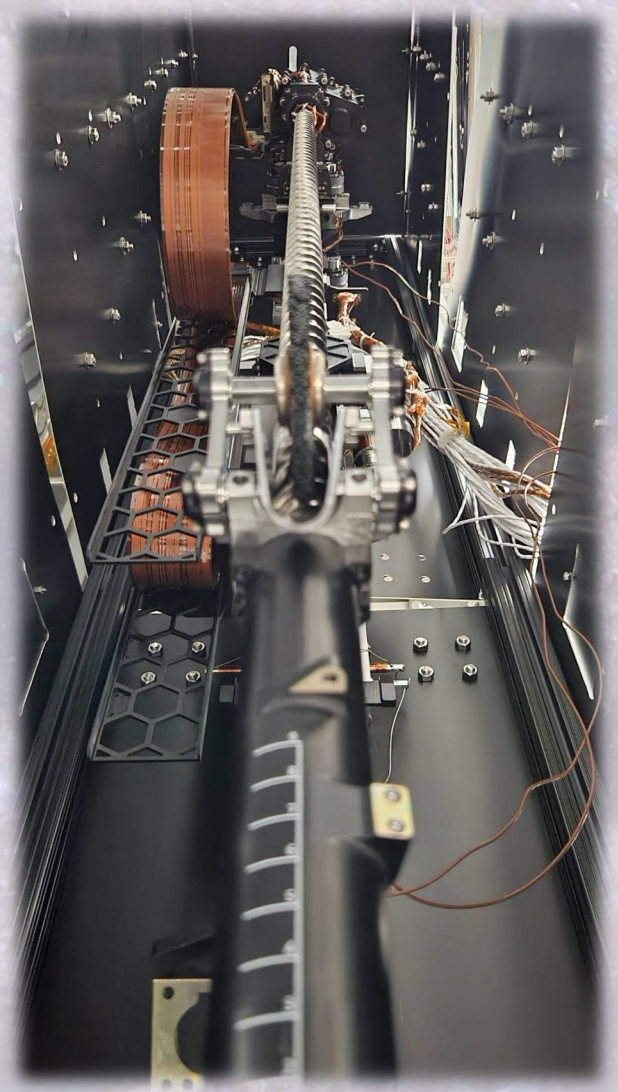


TRIDENT Description

- TRIDENT (The Regolith and Ice Drill for Exploring New Terrains) subsystem includes the hardware to physically **excavate/extract regolith from the lunar surface up to a depth of 1 meter.**

- Excavation device will be instrumented to **measure forces/displacements** in order to determine critical bulk properties of the regolith. This information will be used to understand the working environment and **bound critical excavation parameters for future larger scale regolith mining** equipment and processes.

- TRIDENT captures regolith in **8-10 cm increments** down to a depth of 1 meter. Material captured by the drill is transported to the surface to be analyzed by **MSolo**. TRIDENT measures **strength of the lunar regolith as well as subsurface temperatures** during drilling operations.



TRIDENT Data

TRIDENT Science Data

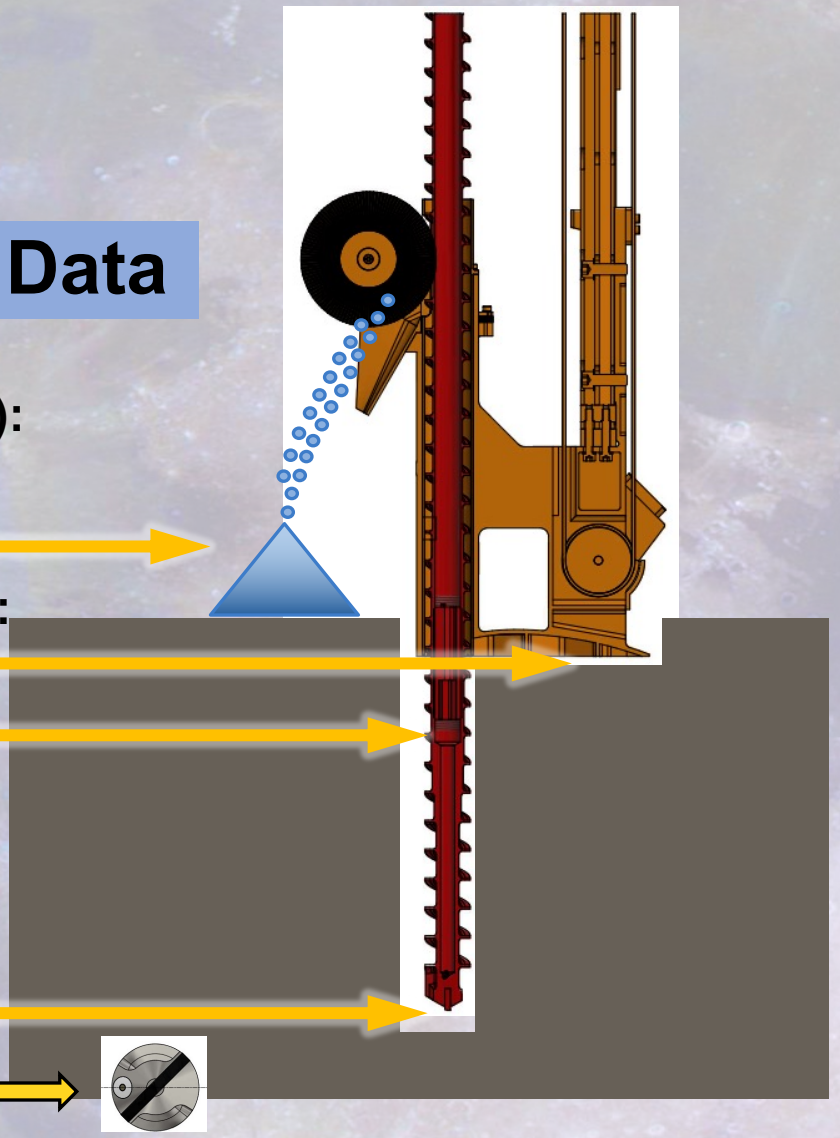
Cuttings cone (*):
- Angle of Repose
- Density at Dr of ~0%

Footpad sinkage provides (#):
- Bearing capacity

Drilling Power (#):
- Material Strength vs. Depth
- Loose ice grains vs ice cemented regolith

Heater (#):
- Thermal Conductivity (with Temp. Sensor)

Bit Temperature Sensor (#):
- Subsurface Temp vs Depth

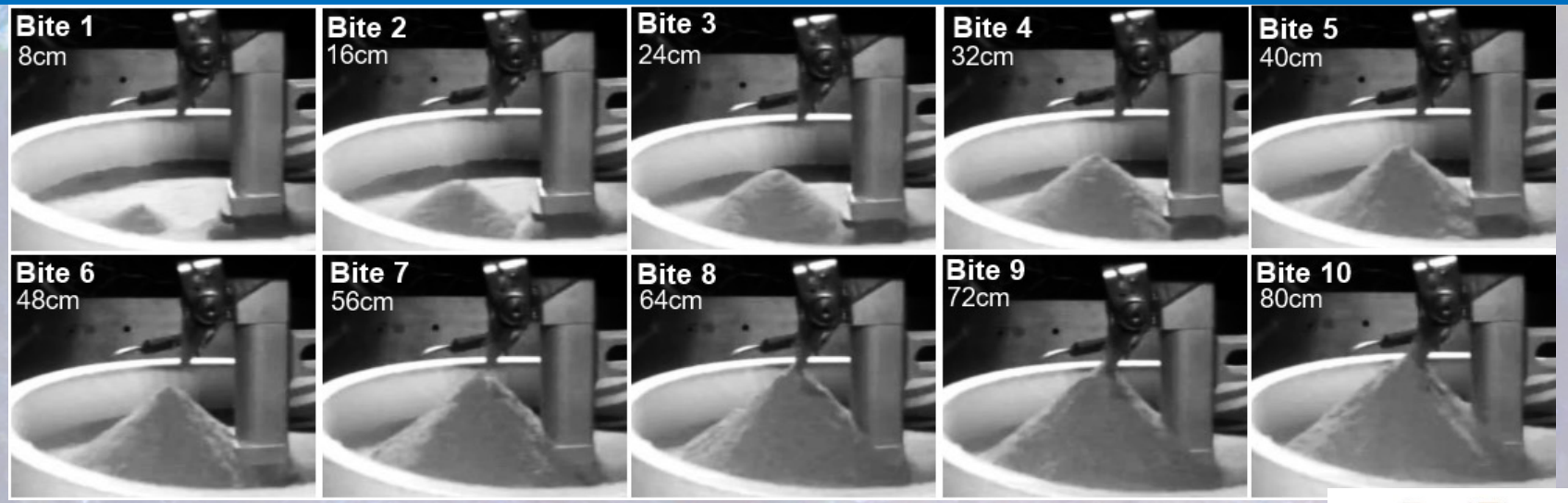


Engineering Specifications

Parameter	Value
Bit Diam. (mm)	**25.4**
Nominal Auger Spin (RPM)	120
Auger Average Output Torque (N-m)	5.5
Auger Average Power Consumption (W)	87
Percussion Impact Energy (Joules/Blow)	2
Nominal Percussion Rate (BPM)*	972
Feed Stage Stroke (mm)	1240
Maximum Drill Depth (mm)	**1020**
Deployment Stage Stroke (mm)	380
Z Stage Force Cont. (N)	500
CBE Drill and Launch Locks Mass (kg)	**~22**
CBE Avionics + Harness Mass (kg)	**~7**

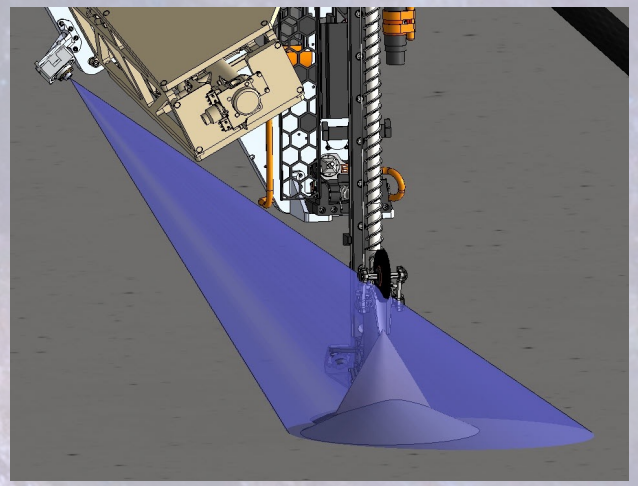
Cuttings Pile

The cuttings pile size increases with each bite, evenly falling into a cone shape on the surface

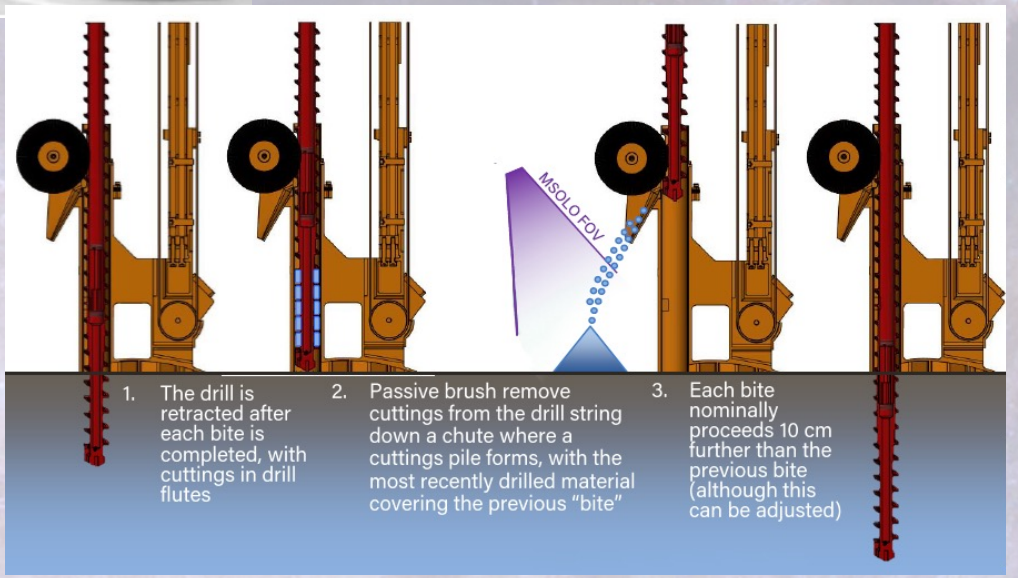


Advantages of Bite Sampling

- Lower Power
- Stratigraphy is preserved in 8-10 cm “Bites”
- Accurate material strength determination
- More accurate downhole temperature
- Reduced risk of freezing-in

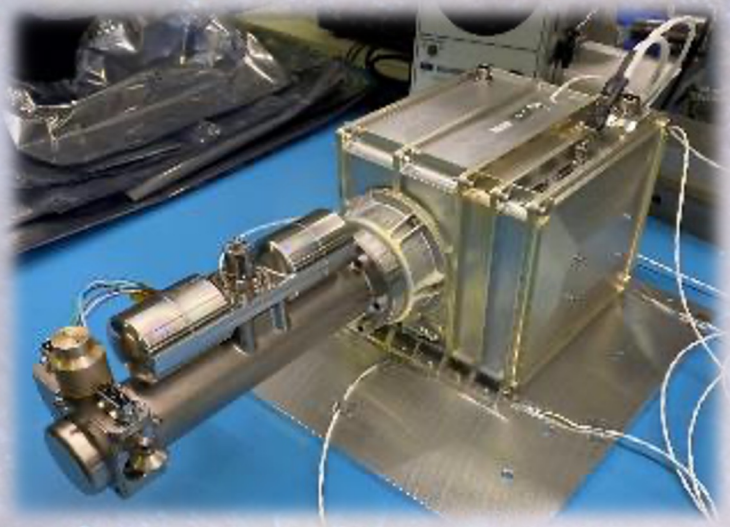


The lander partner provides regular camera imagery of the cuttings pile while operating. Images will be provided every minute during active operations, every 5min during analysis hold periods.



MSolo

MSolo is a modified-for-spaceflight commercial-off-the-shelf (COTS) Mass Spectrometer

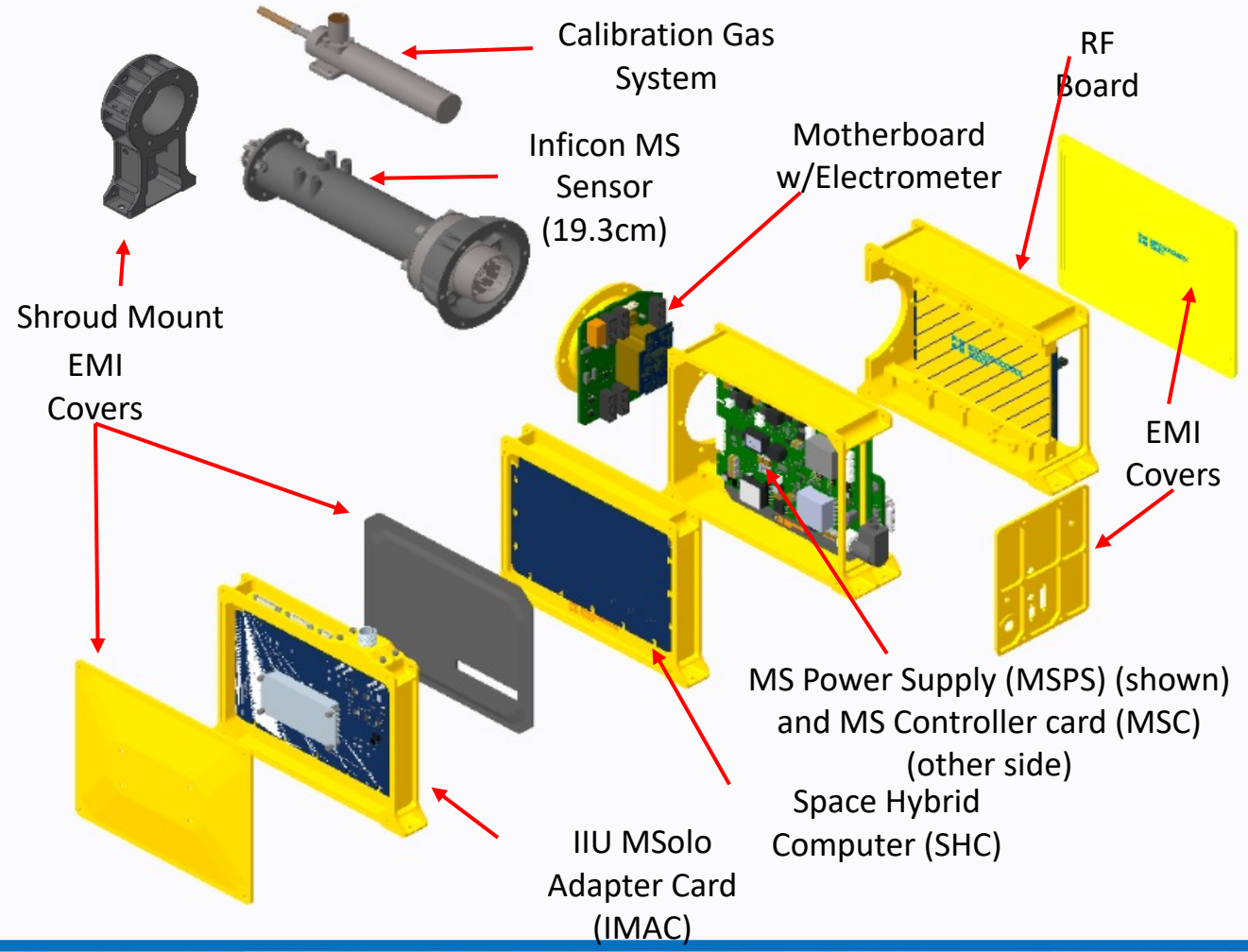


- INFICON Quadrupole mass spectrometer
- Open or Cross Beam Ion Source (COTS)
- Electron impact ionization - Dual Y_2O_3/Ir filaments (COTS)
- Faraday Cup and Electron Multiplier Detectors (COTS)
- Calibration Gas System (KSC)
- Chassis designed to build on instrument avionics and include spaceflight control computer (SHREC) and power board

Cross Beam Ion Source

Open Ion Source

MSolo



Ruggedization for Spaceflight

- Calibration Gas System
- Thermal upgrades
- Structural Upgrades
- Onboard computer designed
- Avionics board redesign
- New chassis to support COTS MS Boards, new power boards and onboard computer
- Software designed to be compatible with RS422 and COTS firmware/operation

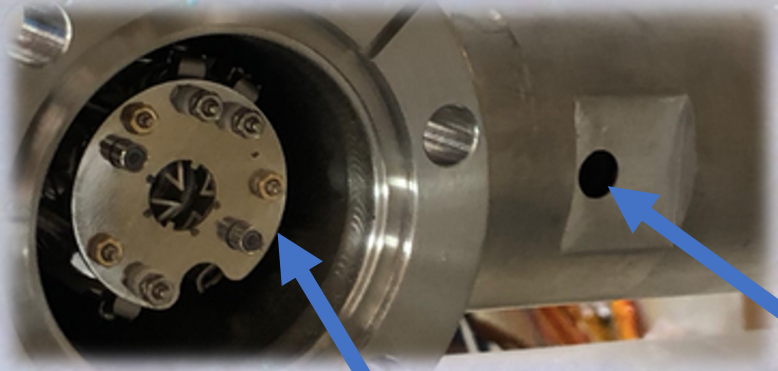
MSolo's Cross Beam Ion Source

- Designed for analysis of molecular or pseudo-molecular beams traveling axially to the sensor
- Less sensitive to overall background gas composition, enhanced directional sensitivity
- Allows accurate sampling of a dynamic system, especially a flux from a particular source
- Apertures in shroud along with the ion source configuration provide increased tolerance to particulate contamination

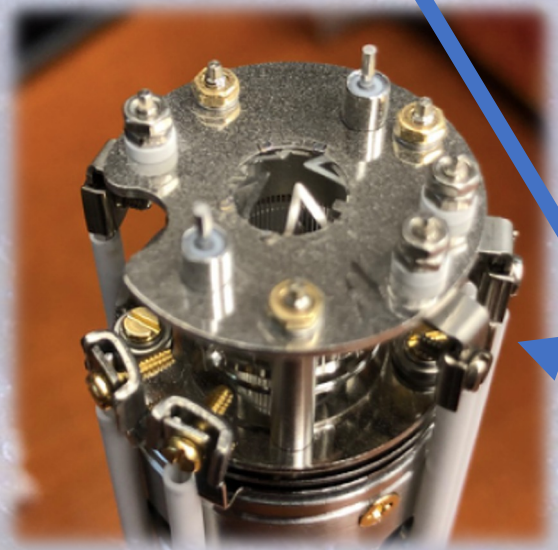
MSolo's Particulate Tolerance

Side-by-side test configuration in GRC VF-13 vacuum chamber

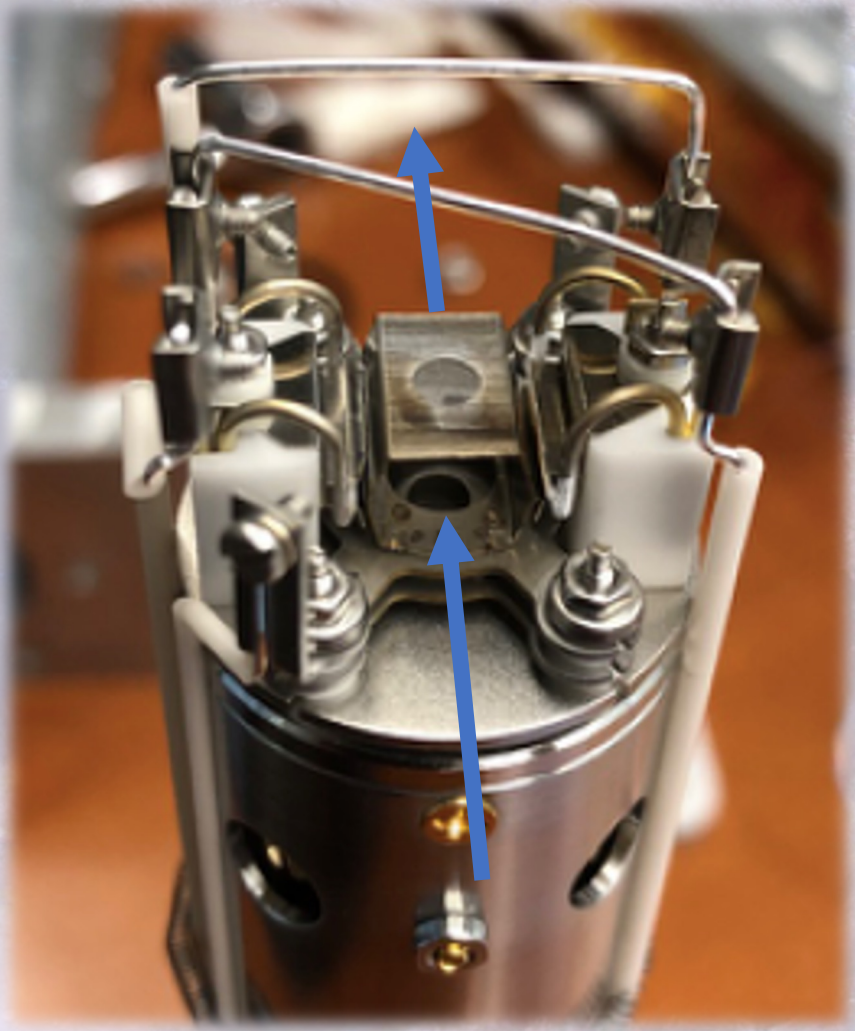
OIS XB



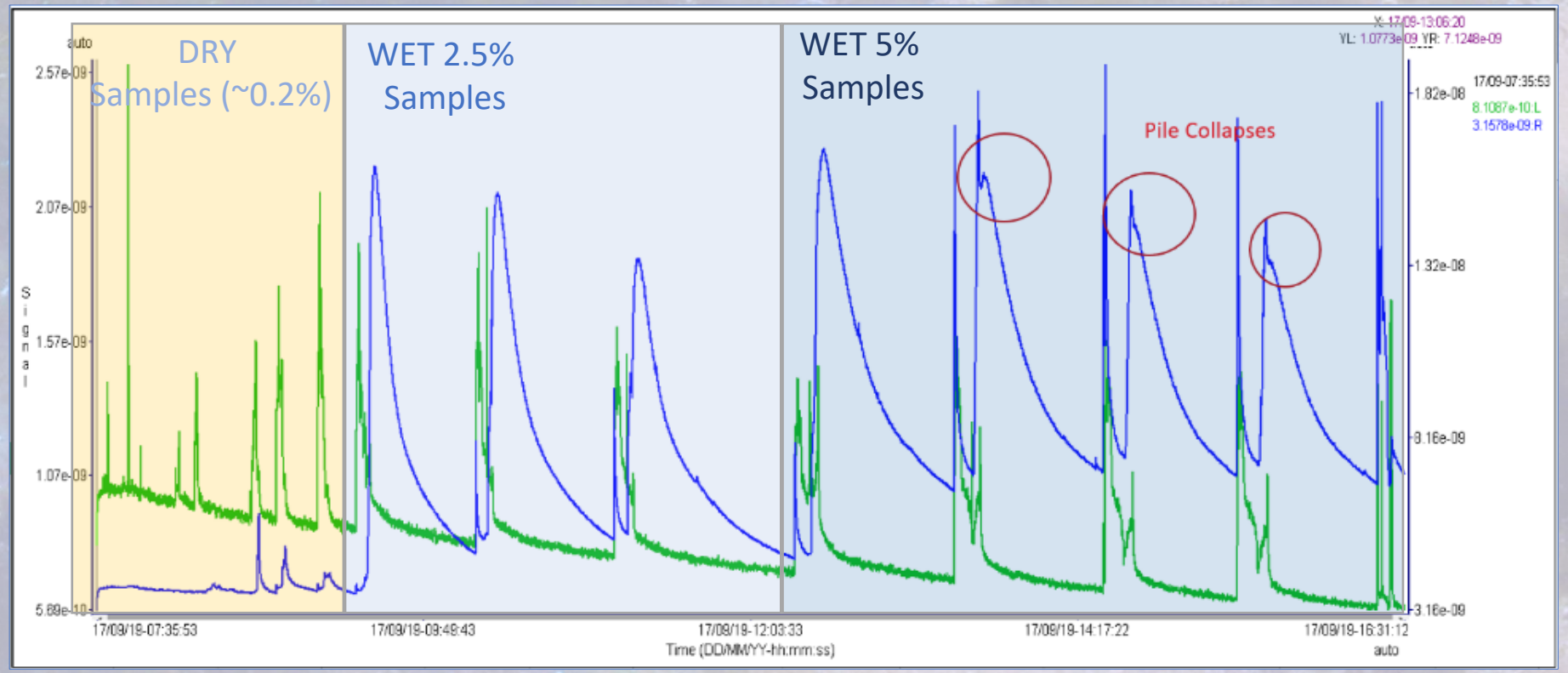
Inlet aperture is aligned with anode cage in crossbeam configuration

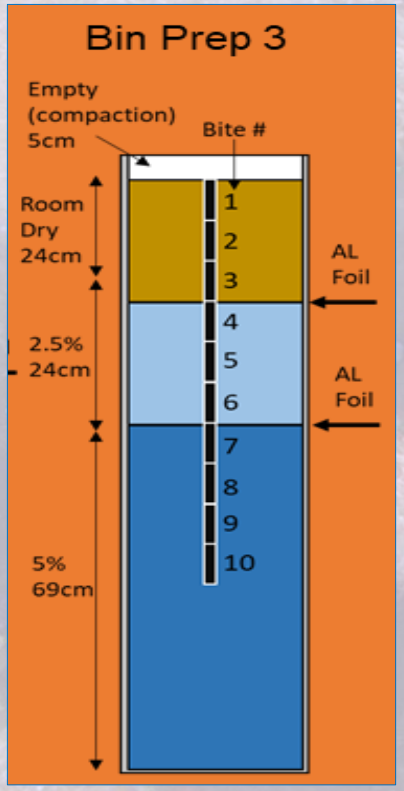


OIS covered in fine layer of simulant after eruption from soil bin, no simulant visually observed on the crossbeam



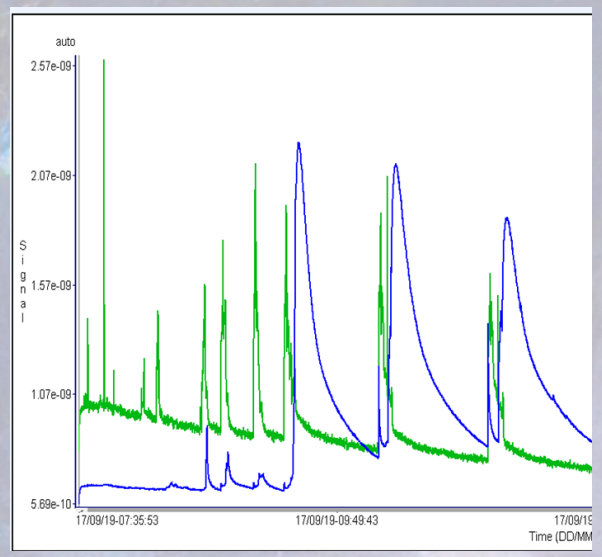
Interpreting MSolo Water Signatures (blue) and Quantification





- TRIDENT Test #5 water signal correlates well with water concentration in layer: Low signal for dry layer bites, large water signals from 2.5wt% water layer and larger signals for 5wt% water in soil brought to surface.
- Pile collapses and drill chute interference with the pile occurs on bites 8, 9 and 10 affecting the quantification of these bites

Long MSolo Analysis Time

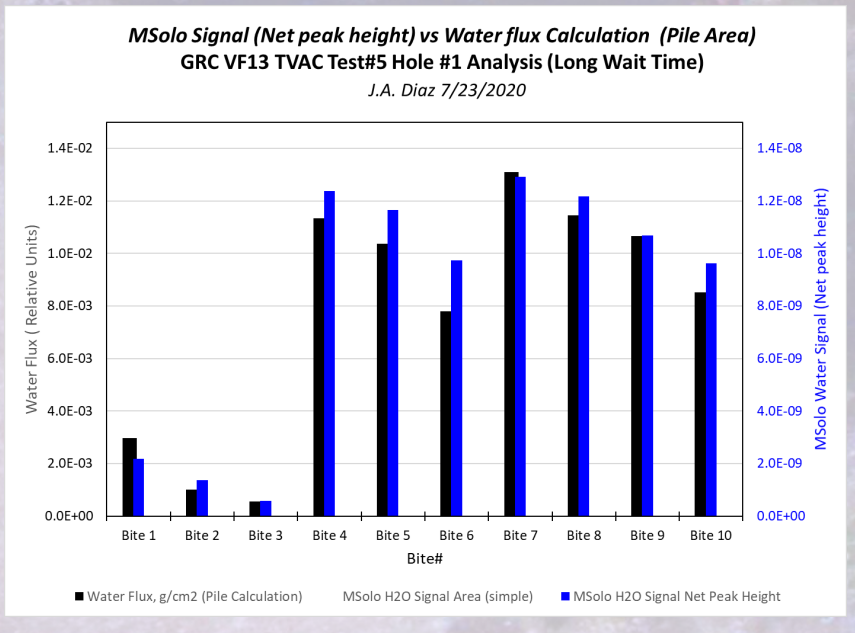


Data from TVAC tests showing water signal decay (blue).

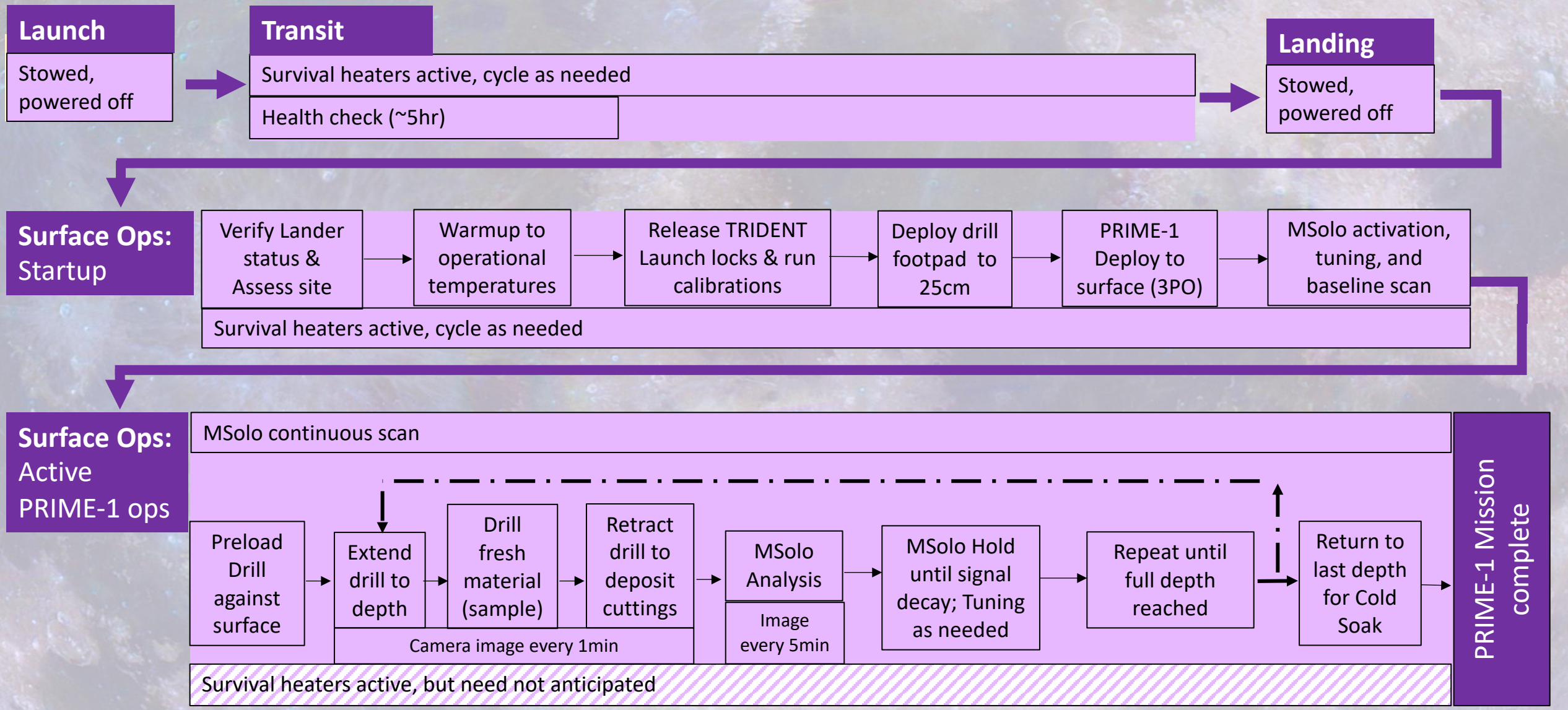
- PRIME-1 will be able to implement a long MSolo analysis time, looking at the water signal decay which is used to:
  - Understand the volatile diffusion and desorption from regolith which informs ISRU – i.e. desorption during excavation
  - Apply the diffusion model developed using Earth-based TVAC conditions for quantification of PRIME-1 observed lunar water
- In the VIPER mission, the timeline does not allow for the full signal decay
  - The peak intensity will be used to interpret the water estimates using the model developed with PRIME and ground test

Water Quantification Estimate:

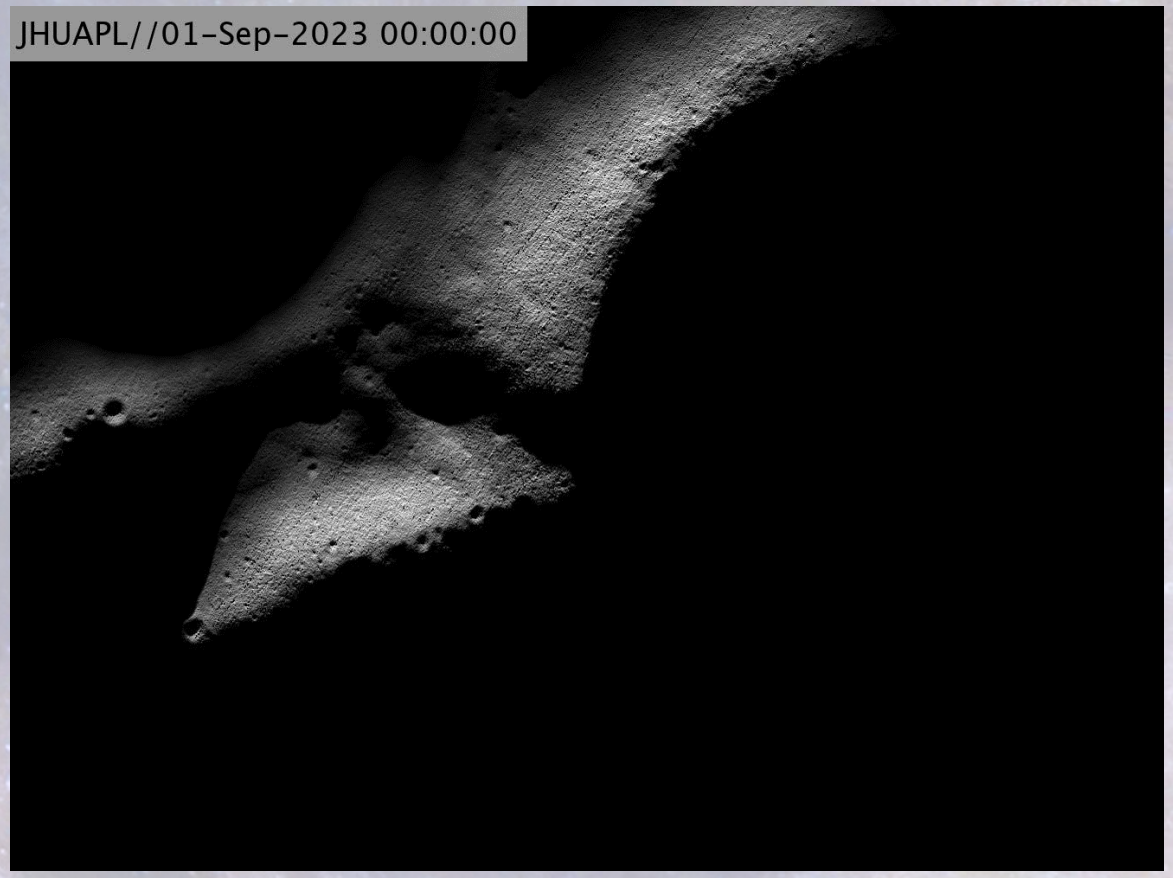
- TVAC tests correlate peak water signal with water flux.
- Water flux is dependent on conical surface area of each bite.



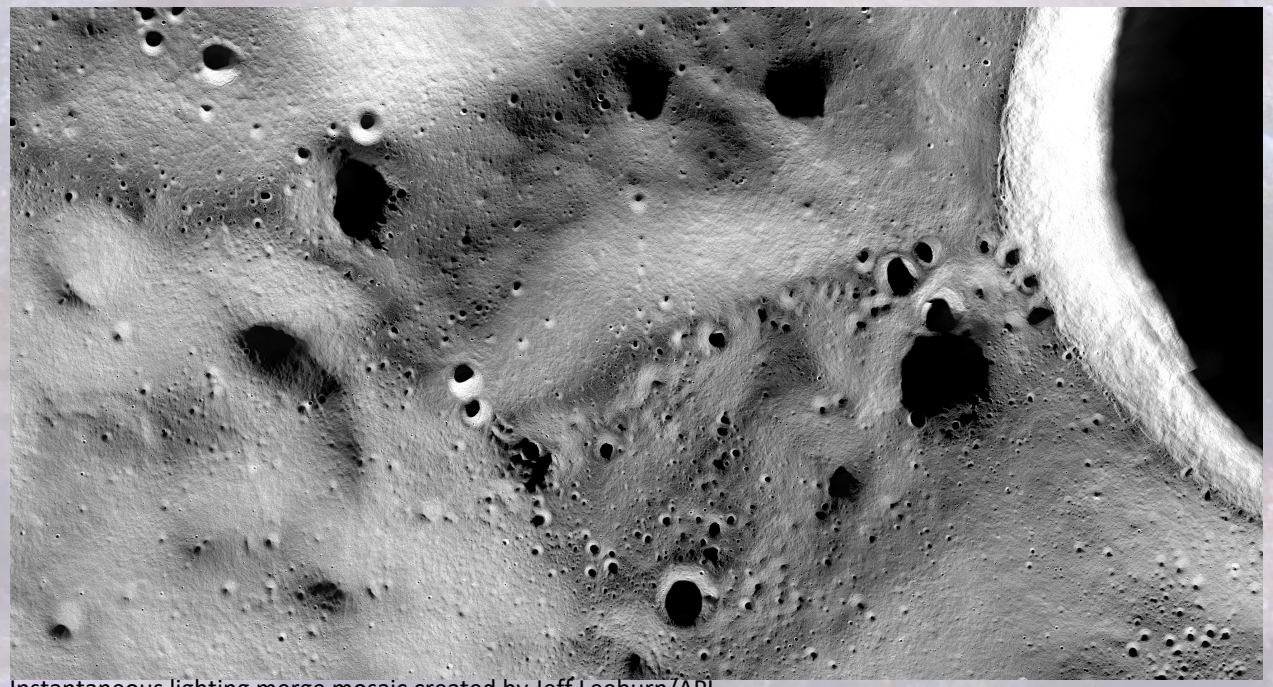
PRIME-1 Operations Flow



PRIME-1 Landing



Video credit Angel Stickle/APL



Instantaneous lighting merge mosaic created by Jeff Leeburn/APL

- Shackleton's Connecting Ridge
- Late 2023
- Intuitive Machines Nova-C Lander
- Falcon 9
- PRIME-1 payload operations approximately 72 hours in duration

Thank You

The work presented herein would not be possible without support from:

- NASA's Space Technology Mission Directorate (STMD), including The Game Changing Development Program and The Small Business Innovation Research Program
- NASA’s Science Mission Directorate, including Commercial Lunar Payload Services (CLPS) and SSERVI
- Honeybee Robotics’ Internal Research And Development (IRAD) Program
- Employees from NASA, Honeybee, Blue Sun, INFICON, Intuitive Machines and other companies who made this effort happen