INSTRUMENTS, DRILLS, AND GEOTECHNICAL SYSTEMS FOR LUNAR EXPLORATION

HONEYBEE ROBOTICS
A BLUE ORIGIN COMPANY

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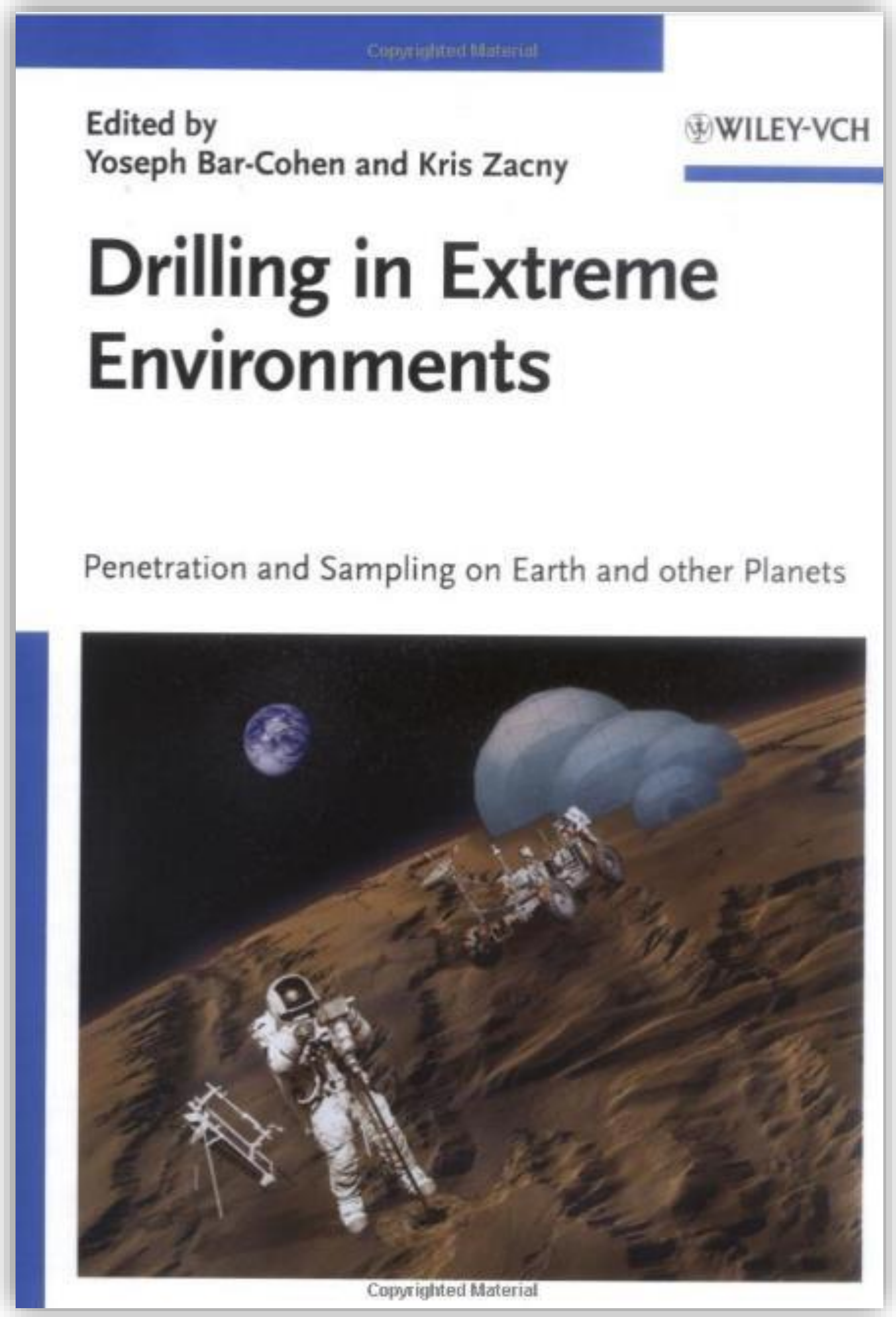
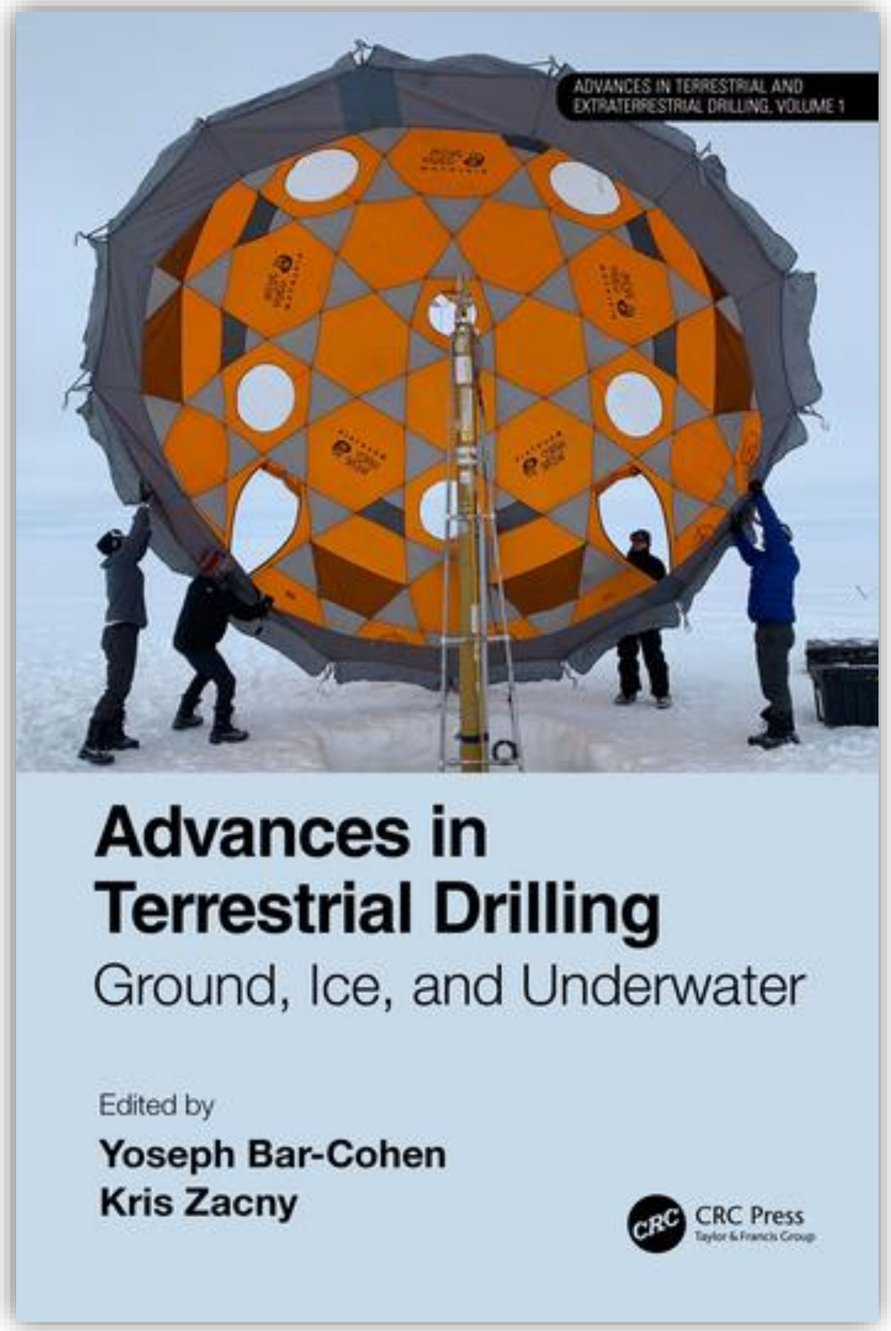
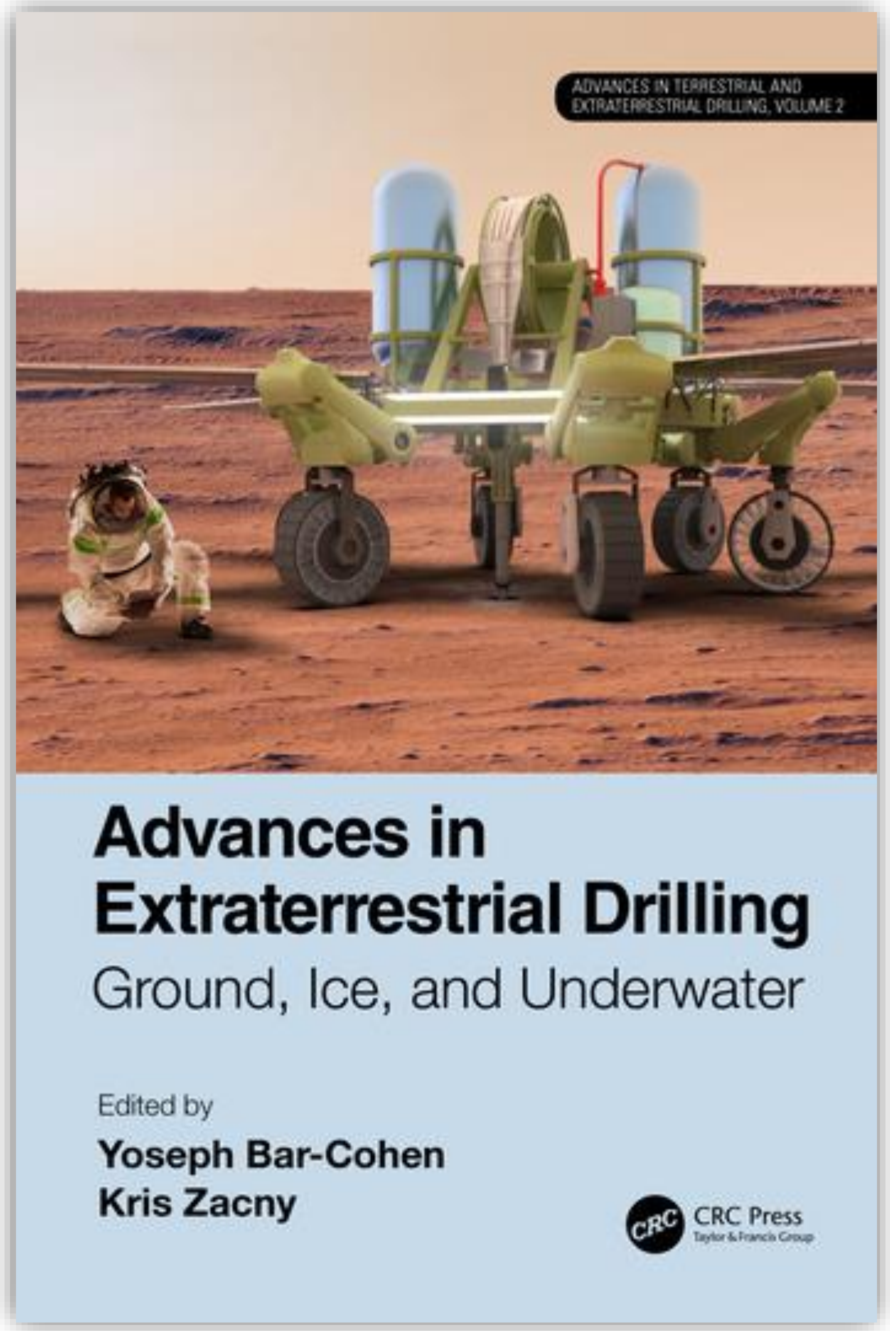
VP, EXPLORATION SYSTEMS

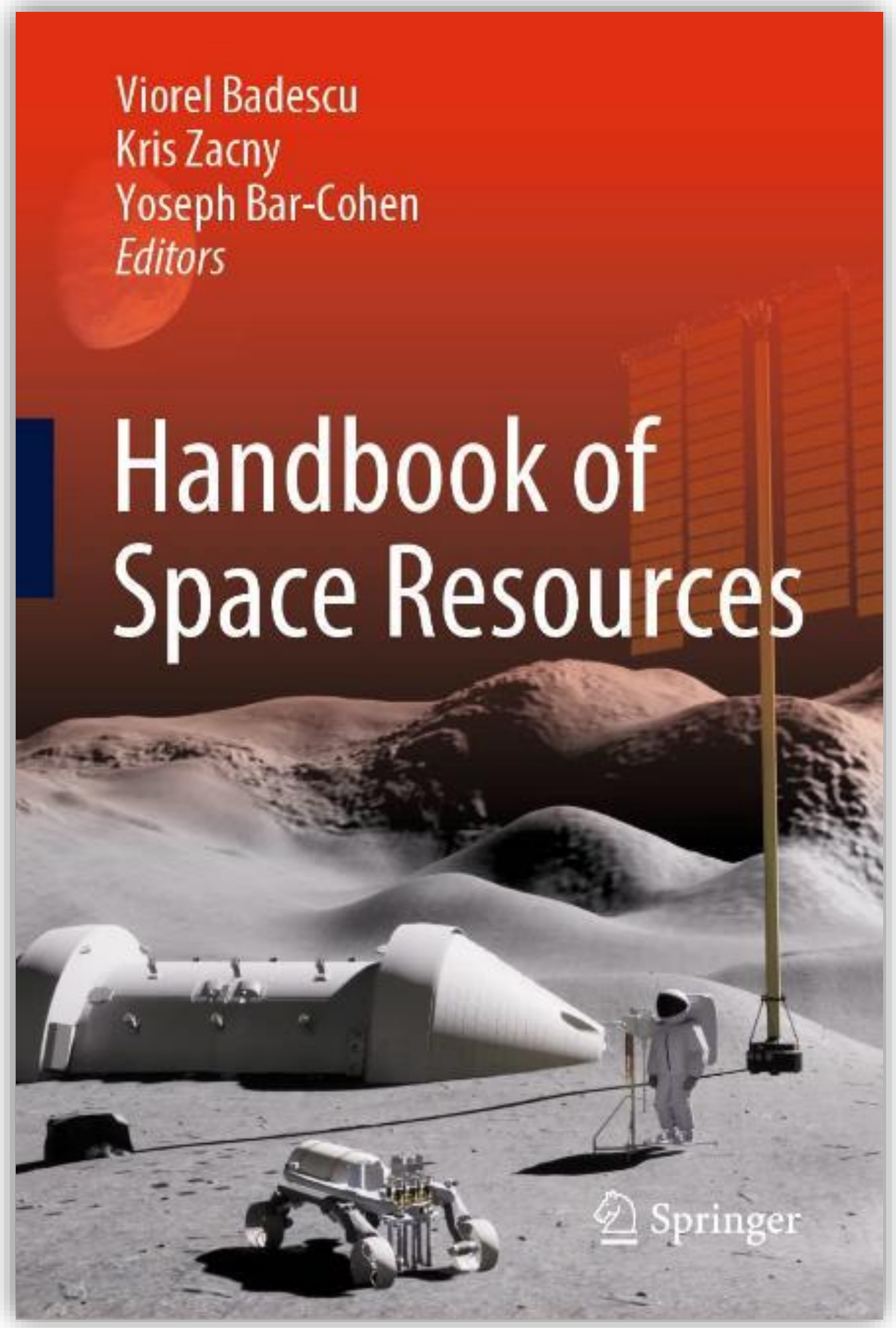
Disclaimer

- Opinions / Recommendations presented here are mine and mine alone
- Technologies presented here have been:
  - funded by numerous NASA programs and Honeybee's IRAD, unless otherwise noted
  - published in various forms, including books







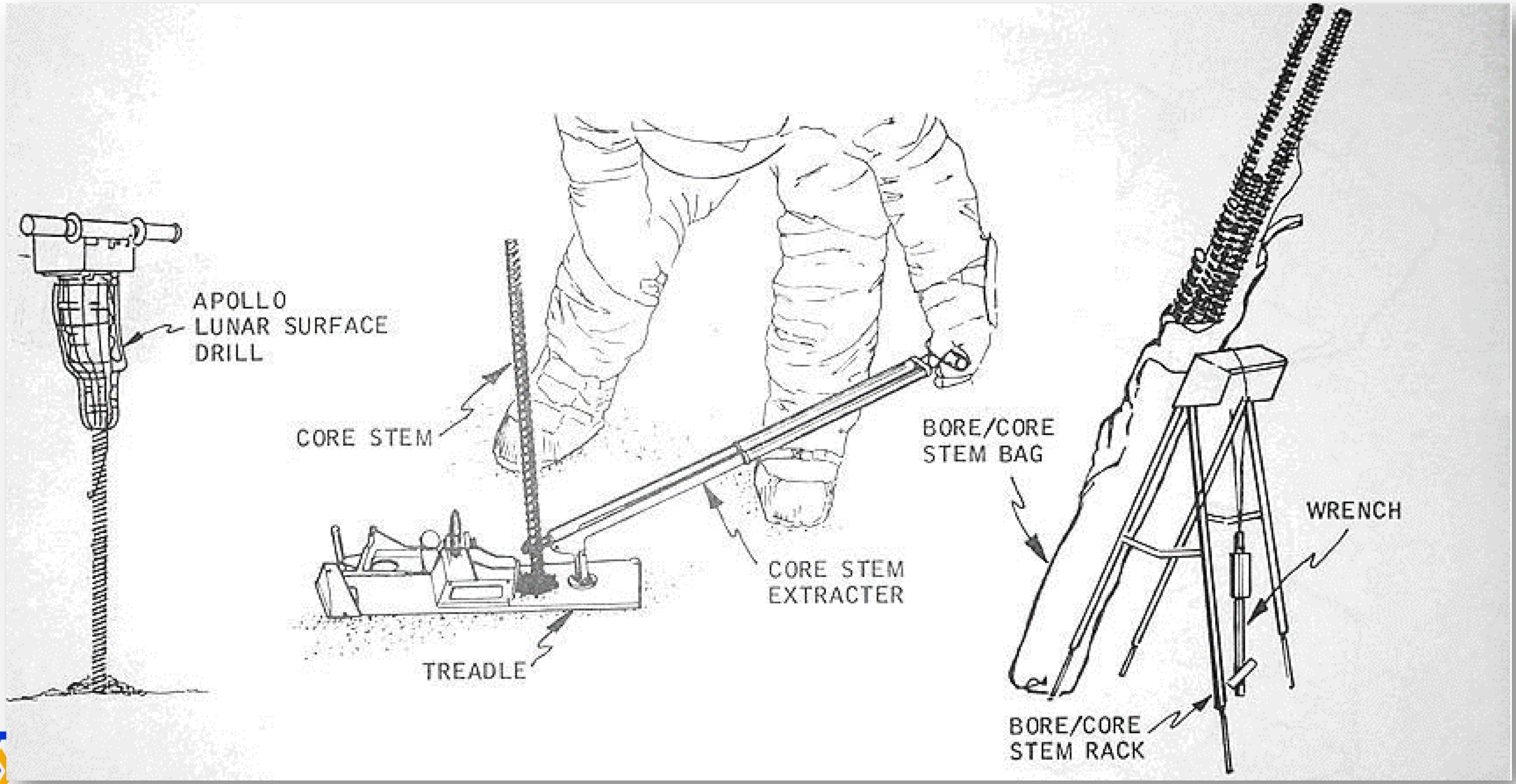


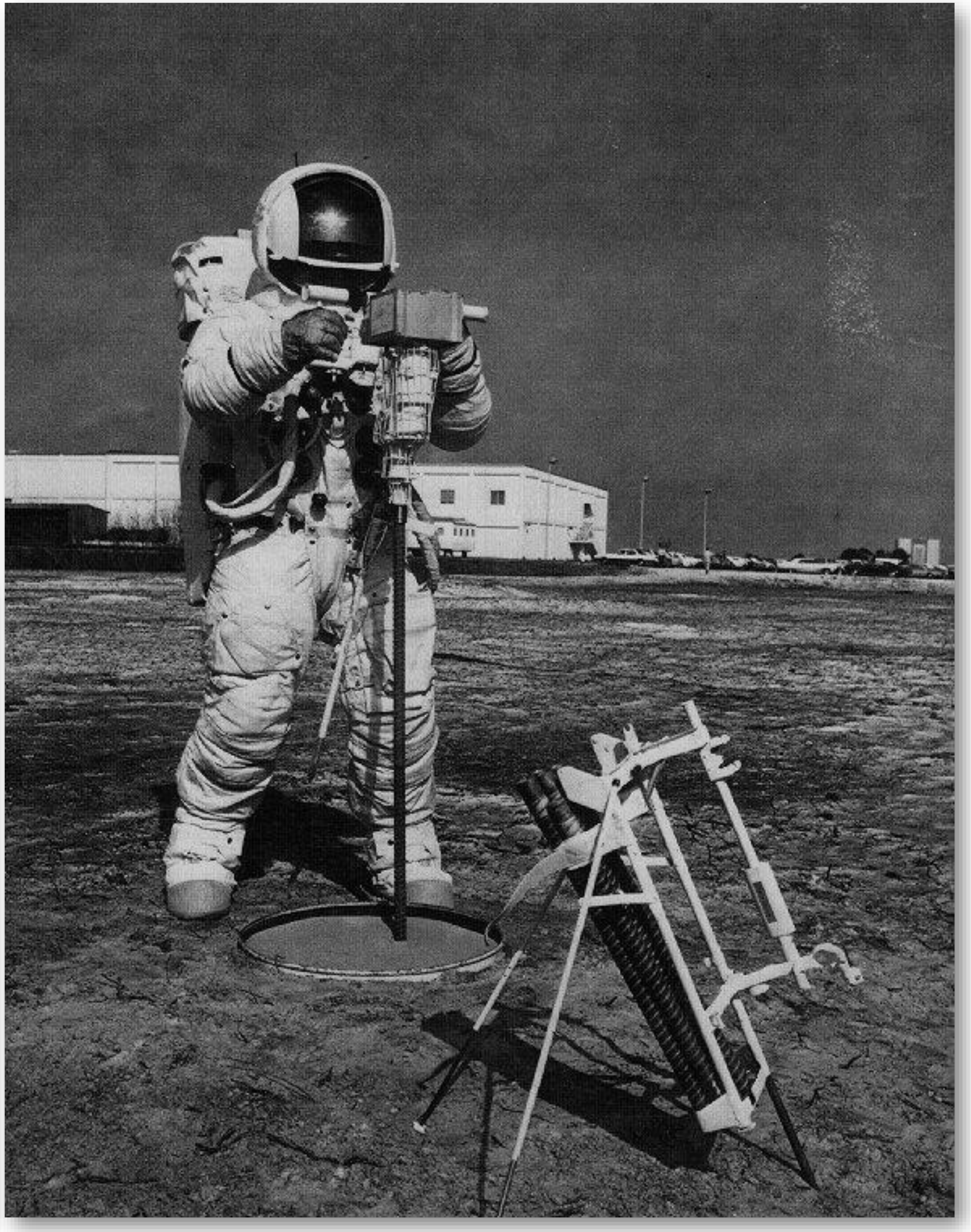
WHAT WE LEARNED FROM:

APOLLO

Apollo Drill

- Battery powered, 450 Watt
- Rotary-Percussive (pressurized drilled head for lubrication and thermal dissipation)
- Used on Apollo 15-17 for:
  - Heat Flow Probe: 2.4 m depth fiber-glass casings (x2)
    - **Problem with drilling beyond 1.5 m on A15**
  - Regolith Core: 3 m depth
    - **Problems with core extraction from 3 m depth on A15-17**





Recap: Lunar soil density vs depth

- Lunar soil becomes very dense very fast
- Dr >90% within first 10s of cm
  - Can not be compacted any more!
- To insert something into the regolith:
  - Crush existing particles: brute force (pile driver)
  - Remove existing particles

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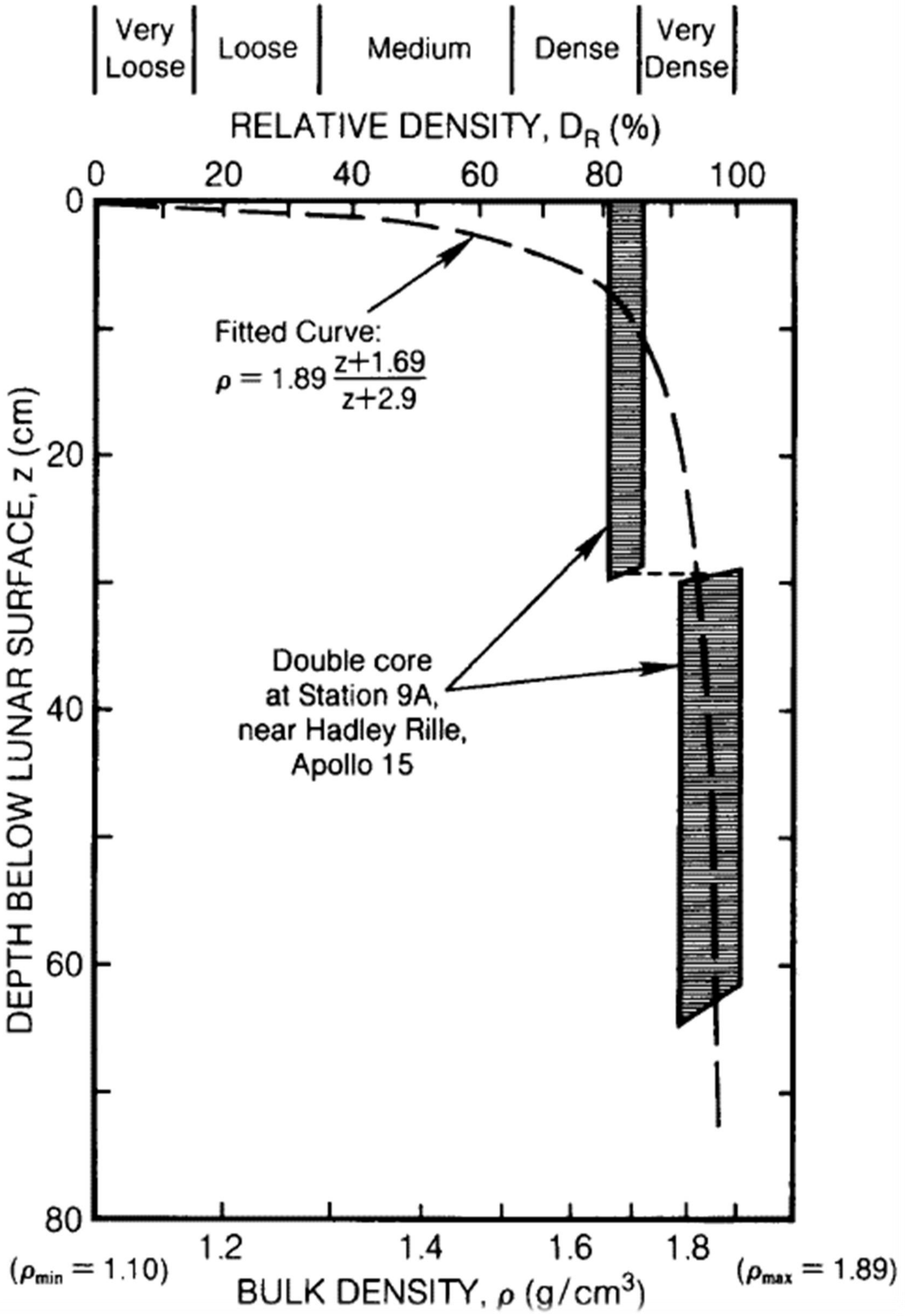


Fig. 9.19. Plots of *in situ* bulk density (bottom horizontal axis) and relative density (top horizontal axis) as a function of depth in the lunar soil layer at the Apollo 15 landing site (Hadley Rille), based on data from core tube samples (Fig. 9.11) and detailed studies of soil sample 15601,82 (Table 9.7) (after *Carrier et al.*, 1973a,b). The soil, although less dense near the surface (<10 cm deep), quickly becomes "dense" to "very dense" with depth (>20 cm).

Heat Flow Probe Instrument

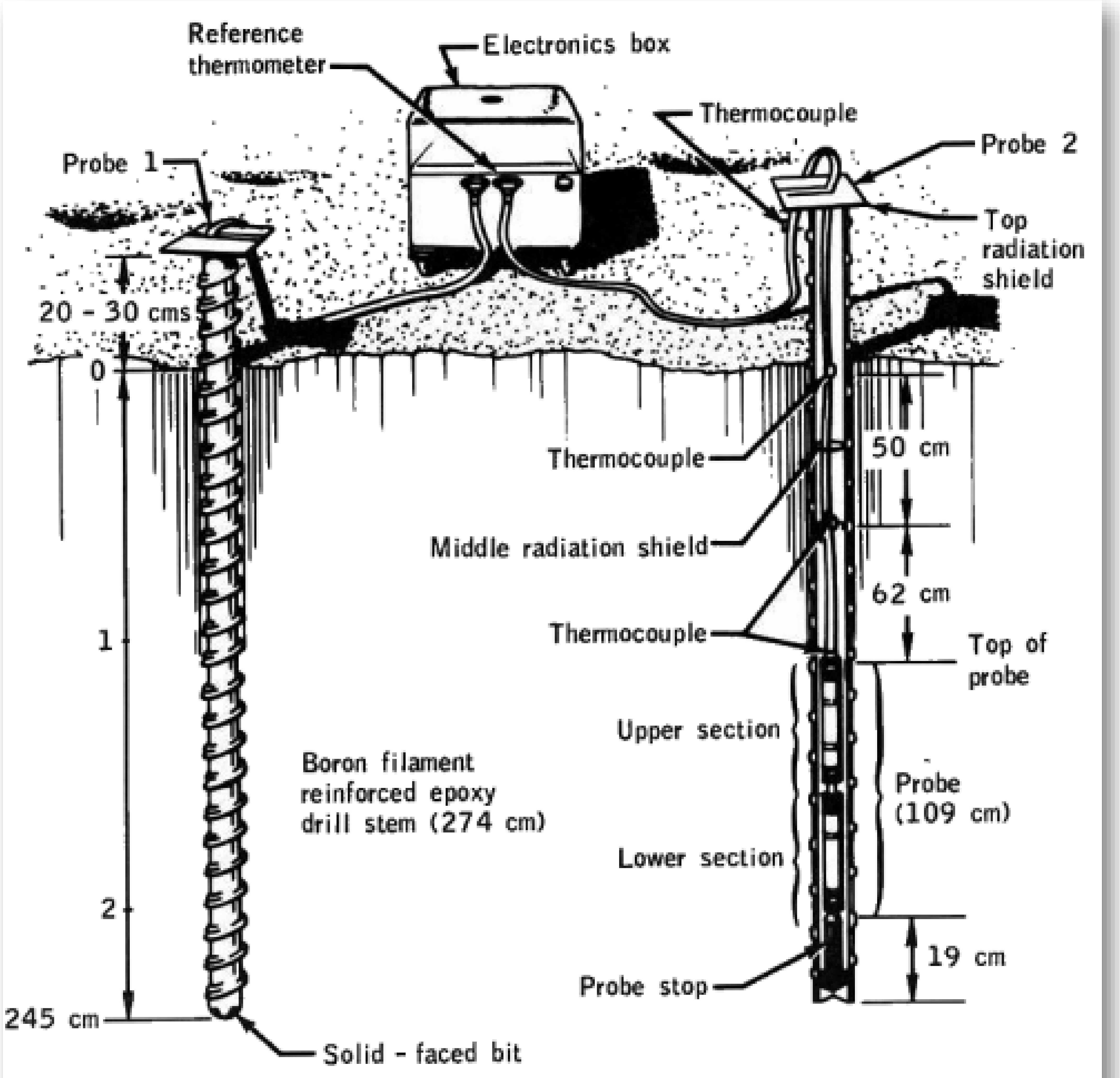


Figure 4-4.- Relative locations of heat flow probes.

A15 HFP: Drilling issue

- Boron fiberglass hollow auger (low k) with full faced drill bit (allow insertion of a probe in a hollow auger)
- Flute designs at the joint was an issue on A15. Redesigned for A16 and A17 (Ti insert, science compromised)
- On A16, Astronaut tripped over the wires and damaged connector. No data.

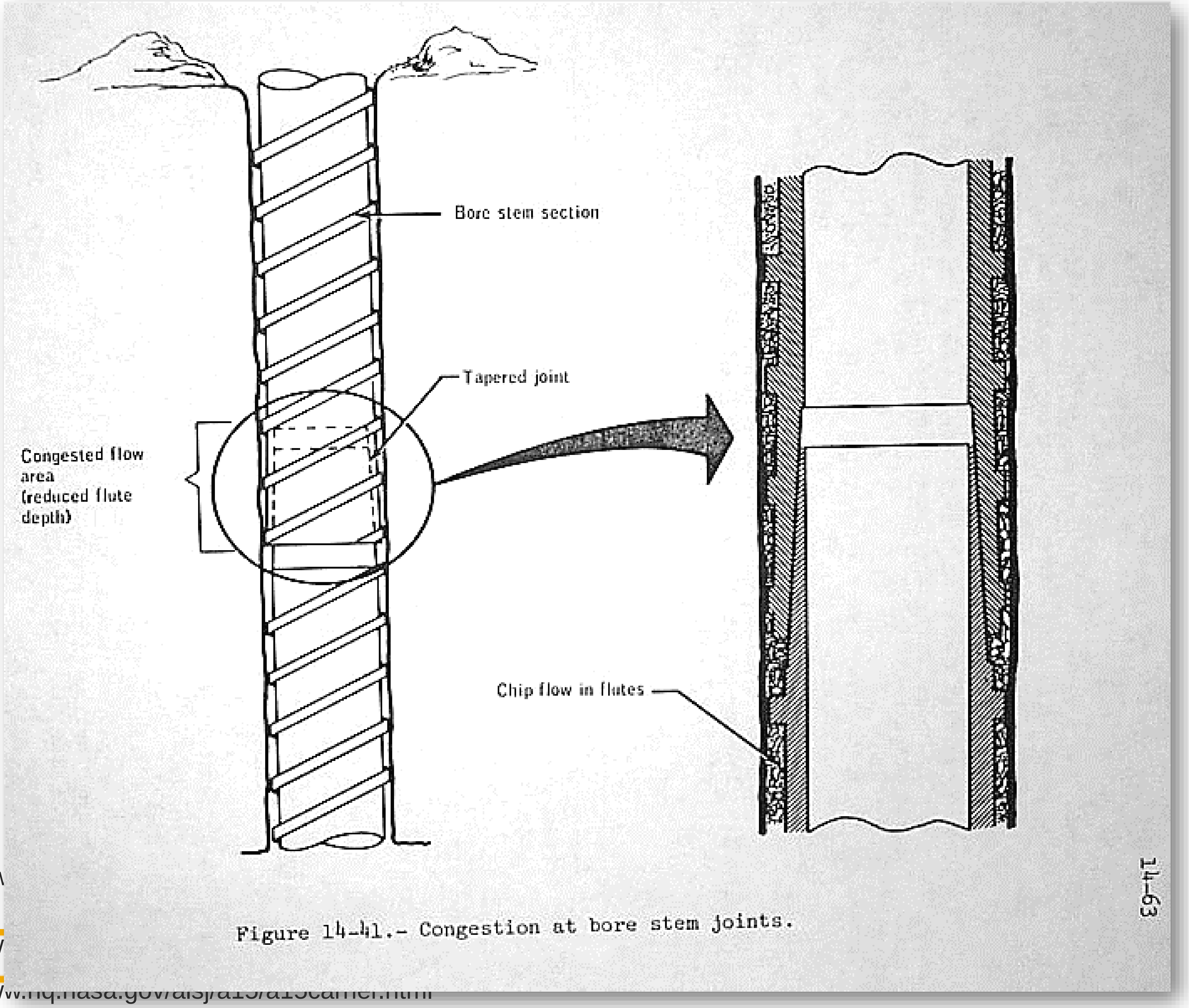
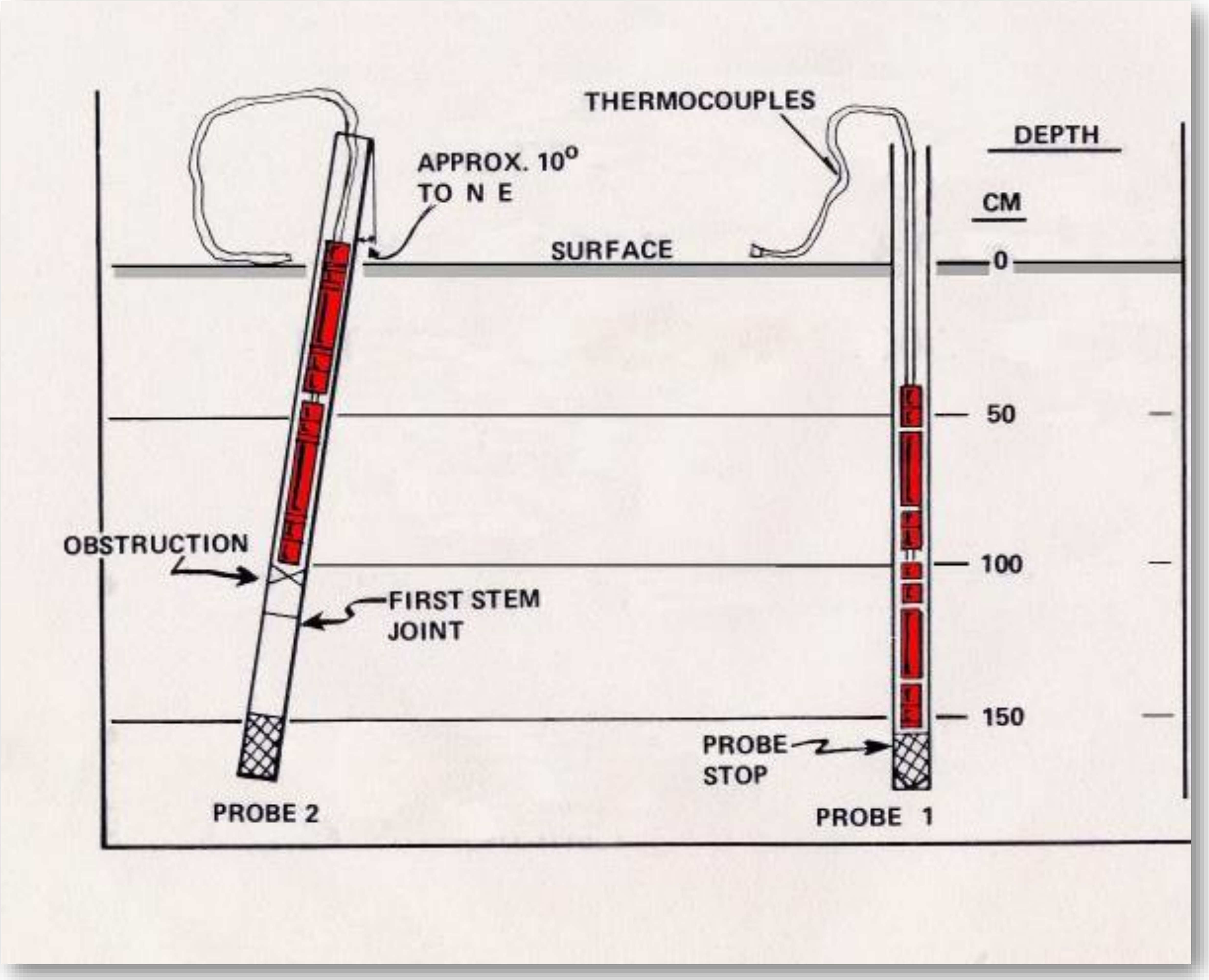


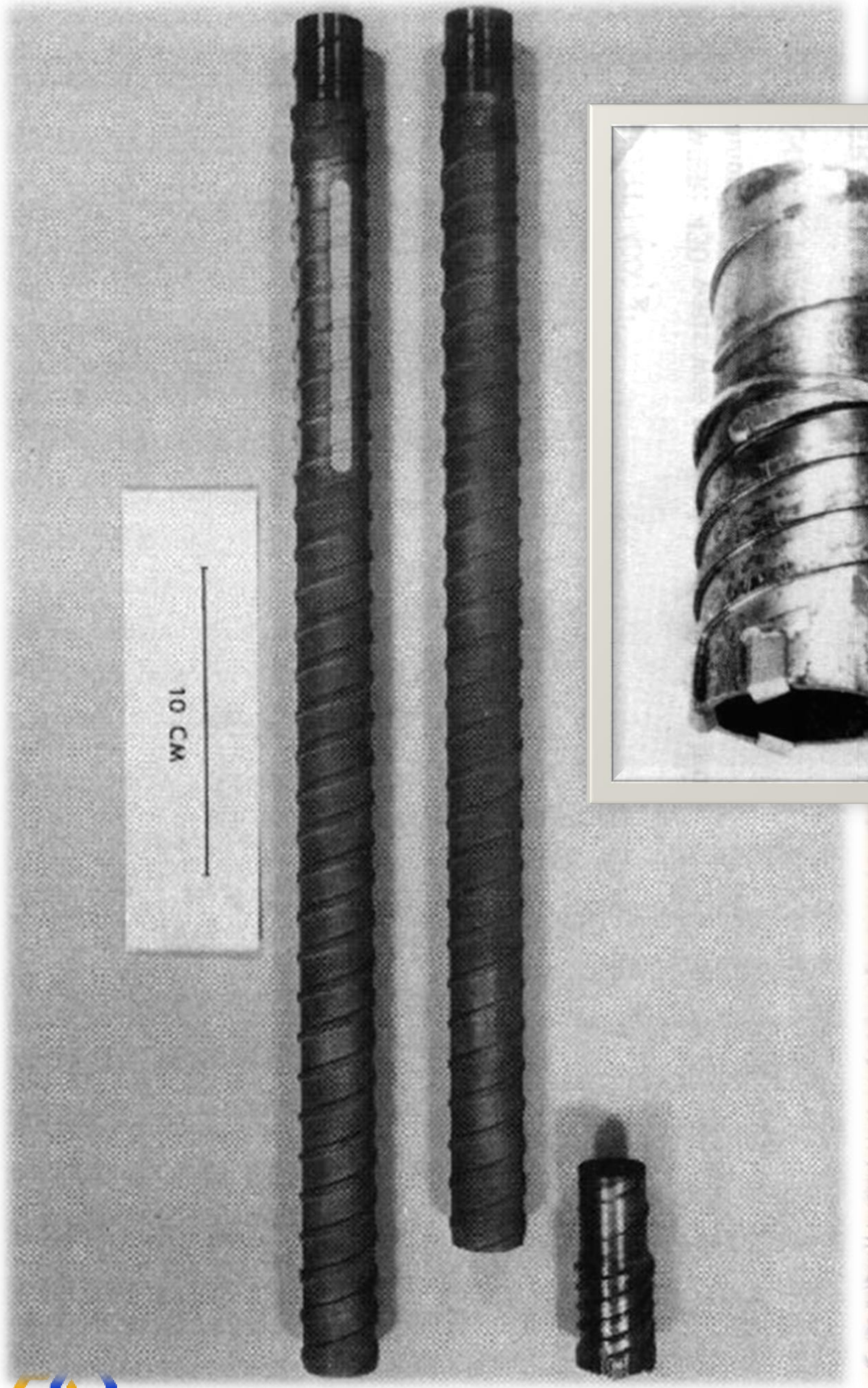
Figure 14-41.- Congestion at bore stem joints.

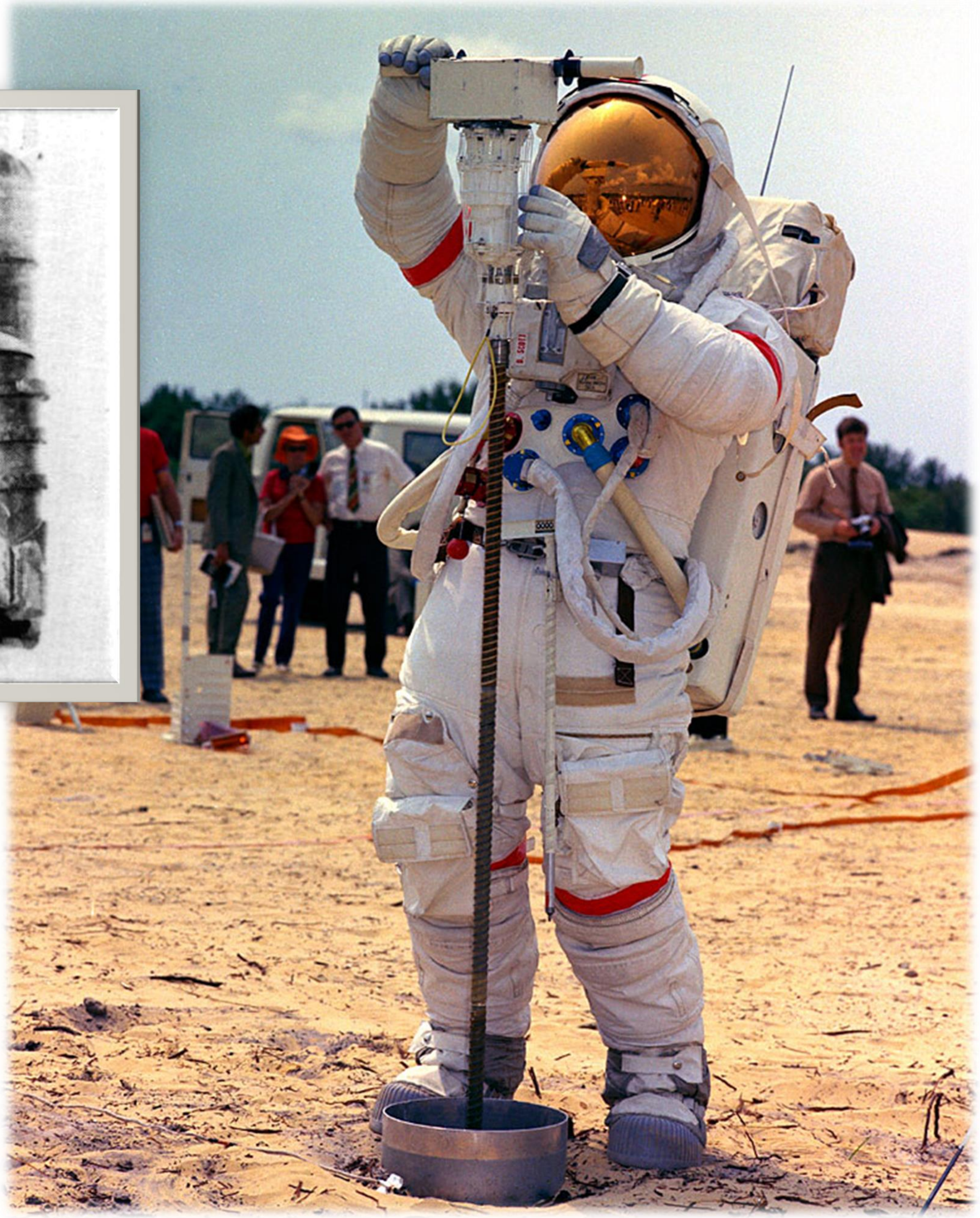


https://w
https://ww
https://www.hq.nasa.gov/alsj/a15/a15camer.html

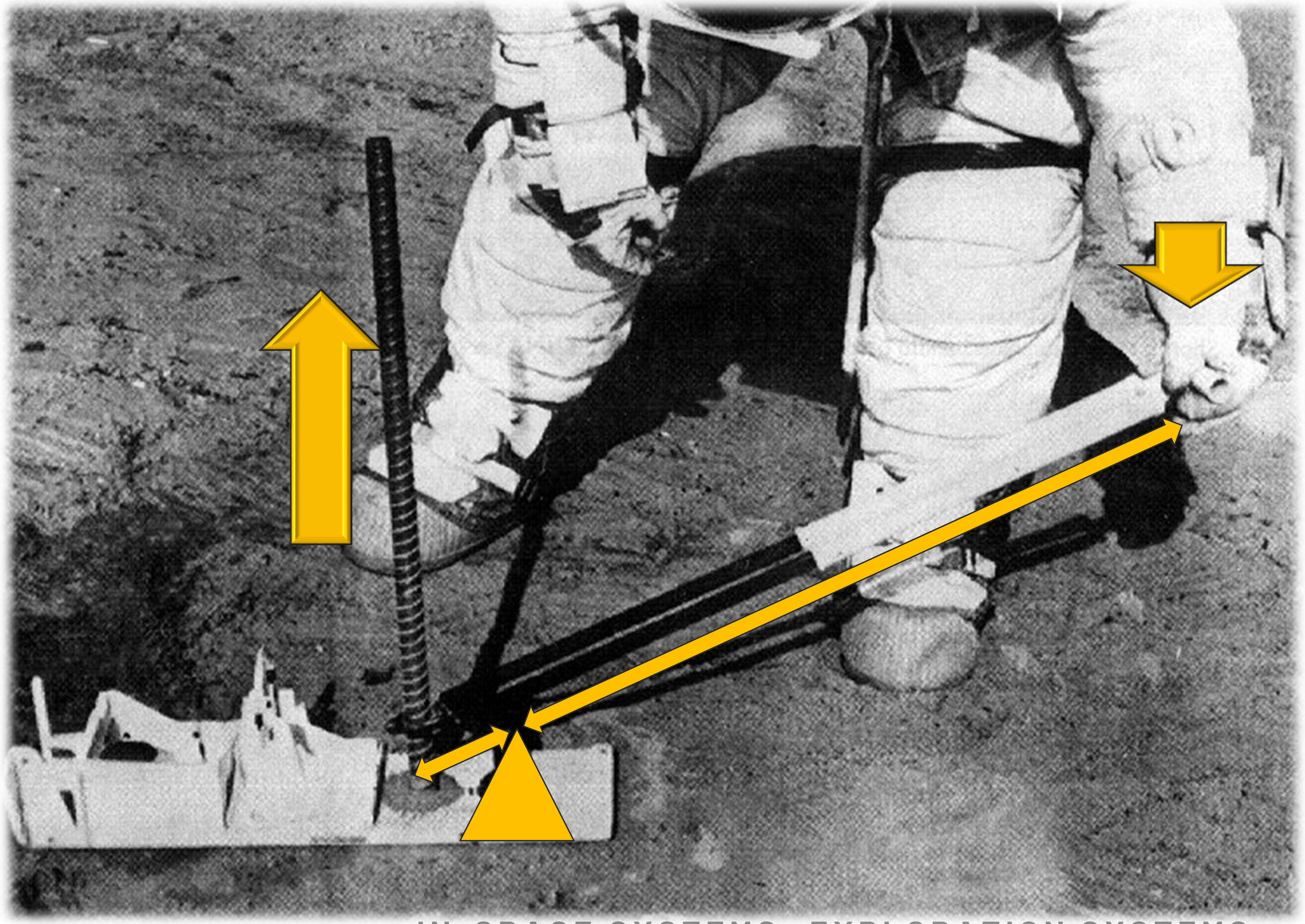
A15-17 Coring to 3 m depth

- Drilling was not an issue
- Core extraction was big issue. A16-17 used a core stem extracter with 60 lb (astronaut) force



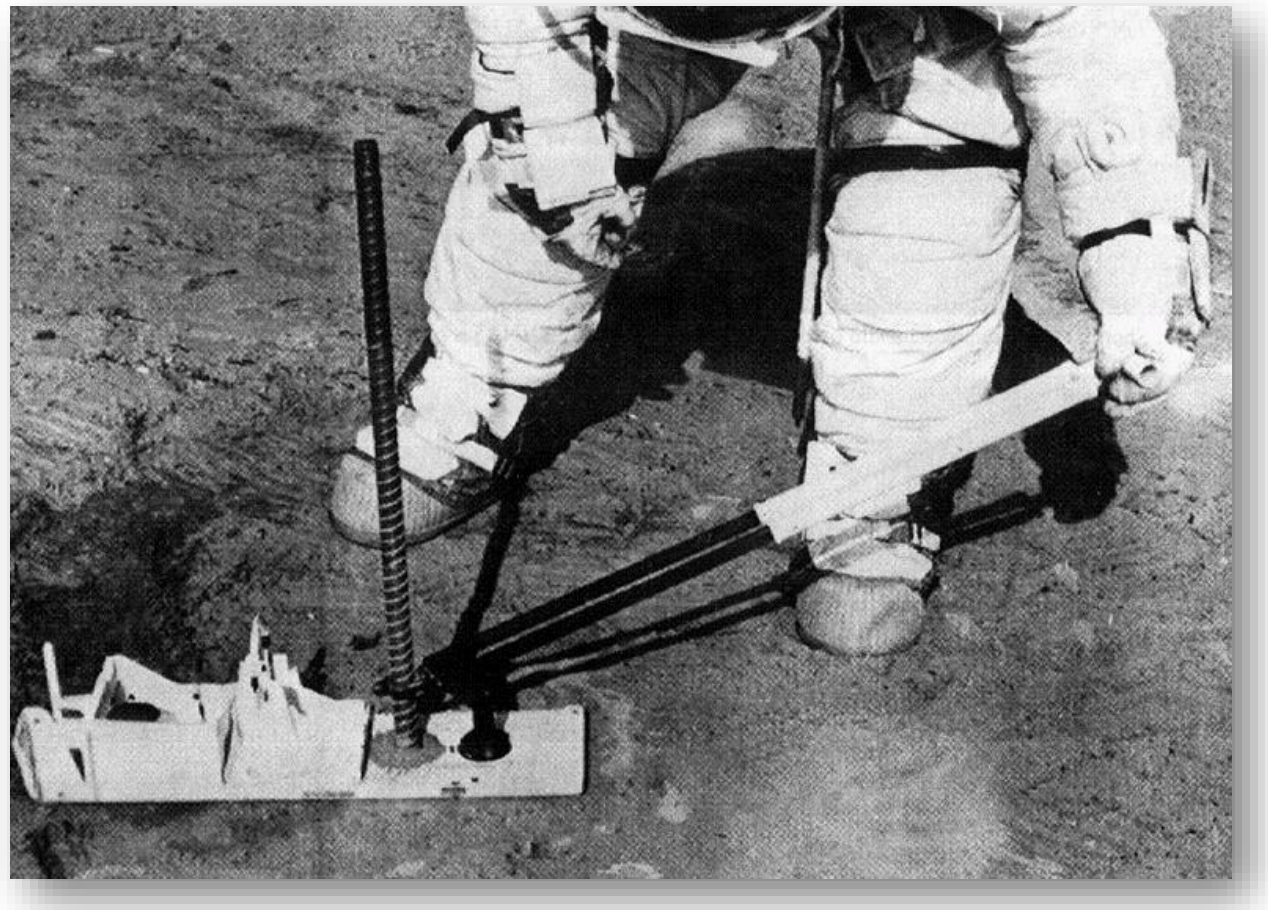


Core stem extracter



Pulling the drill out

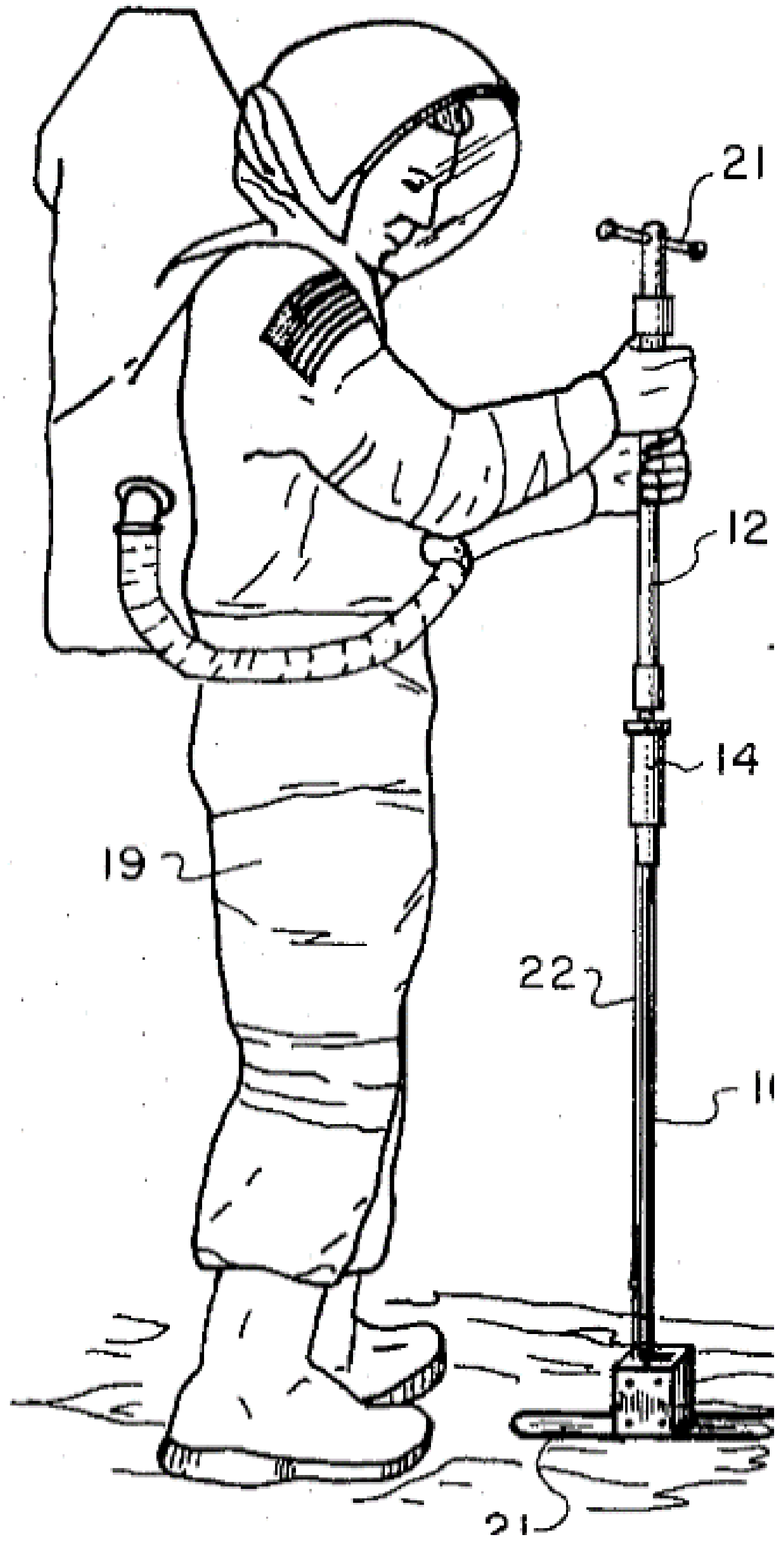
- Corkscrewing causes poor chips removal
- A15: Both astronauts working at the limit to pull up the drill…severe shoulder sprain in Scott
- A17: Throughout the core drilling and extraction, Gene's heart rate has been over 130 beats, with excursions to 145

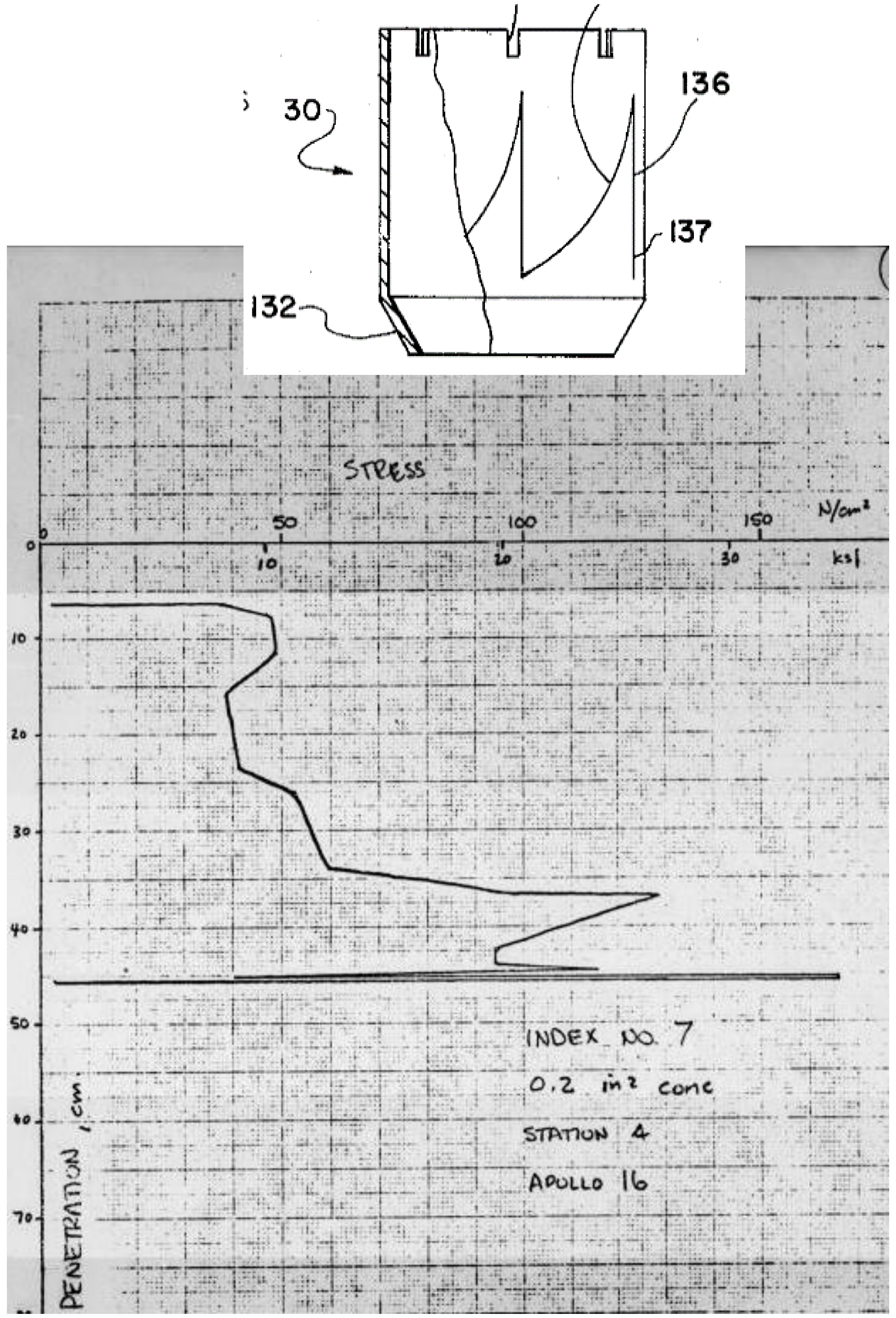


Apollo Geotechnical Penetrometer

Self-Recording Penetrometer

- Manually pushed cones (max 200 N force)
- Cone diameters: 12.8 and 20.3 mm
- An approximate depth of 20-74 cm (depending on soil strength)

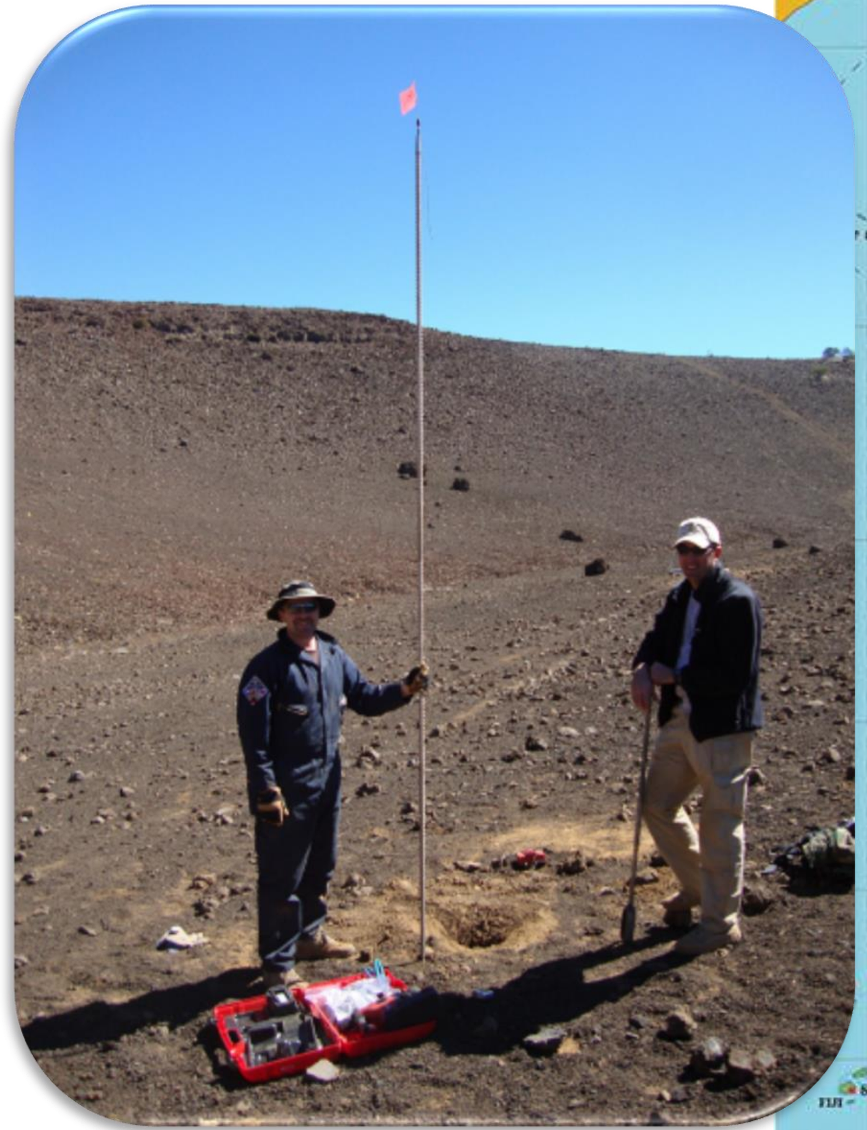




WHAT WE LEARNED FROM:

FIELD DEPLOYMENTS

- Our planet has some good lunar analogs!
- Nature offers "geological uncertainty" → ultimate hardware test
- Operational experience is unparalleled → logistics around "doing stuff" in remote location is eye opening. Majority of time is spent on non-science activities (just like on the Moon!)



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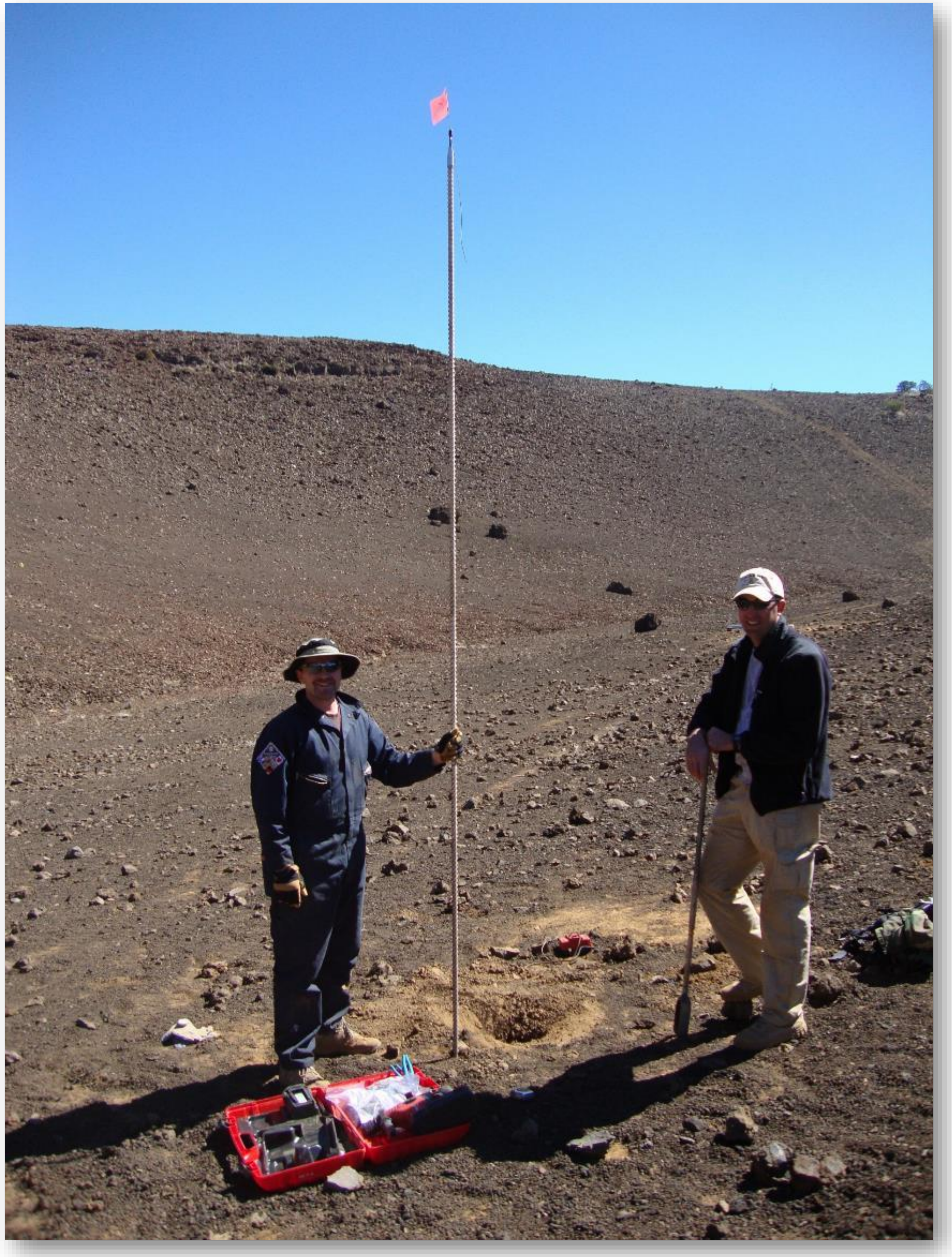
1 m coring on Mauna Kea

- Hilti 750-Watt hammer drill
- 1-inch coring auger - > 1 m depth
- Used Aluminum auger (cheap/fast) with carbide teeth
- After ~10 coring operations, flutes were wearing out, teeth got lost (but still managed to drill!)
- Cohesive soil core would stay inside
- Had to use hammer tapping to get it out

5 m drilling (not coring) on Mauna Kea

- Hilti 750-Watt hammer drill
- 1-inch auger with <u>chisel bit</u> -> 5 m depth (5 x 1 m)
- Very hard work! Got stuck many times. Drill would overheat. Arm would get twisted
- Had to ream to get cuttings out and reduce drilling torque
- Huge corkscrewing effect – had to lift the drill up (apply negative WOB) – otherwise would drill too fast and choke.
- Took ~1 hr



Hole stayed open (just like on the Moon)

Having a vehicle was a huge help!

- Carrying hardware, power etc.
- Could get extra height

Geotechnical tests on Mauna Kea

- Push rod (2-3 cm/sec) - data is questionable if you can't maintain steady penetration rate
- Generates Cone Index (CI)
- Best for weak soils

Geotechnical tests on Mauna Kea

- Uses hammer drill in hammering mode
- Generates CBR
- Can go through hard soils
- Easy to use but requires calibrations

Getting a rock core on the Moon

Core Drilling Kit

CORE DRILL FIELD KIT

Hole Starting

Hold hole starter closed with forefinger and place weight against surface

Begin drilling

Once a groove has been made, release forefinger to remove hole starter

Core Drilling

Drill Clockwise to depth

Drill Counter-Clockwise to break off the core

Sample Removal

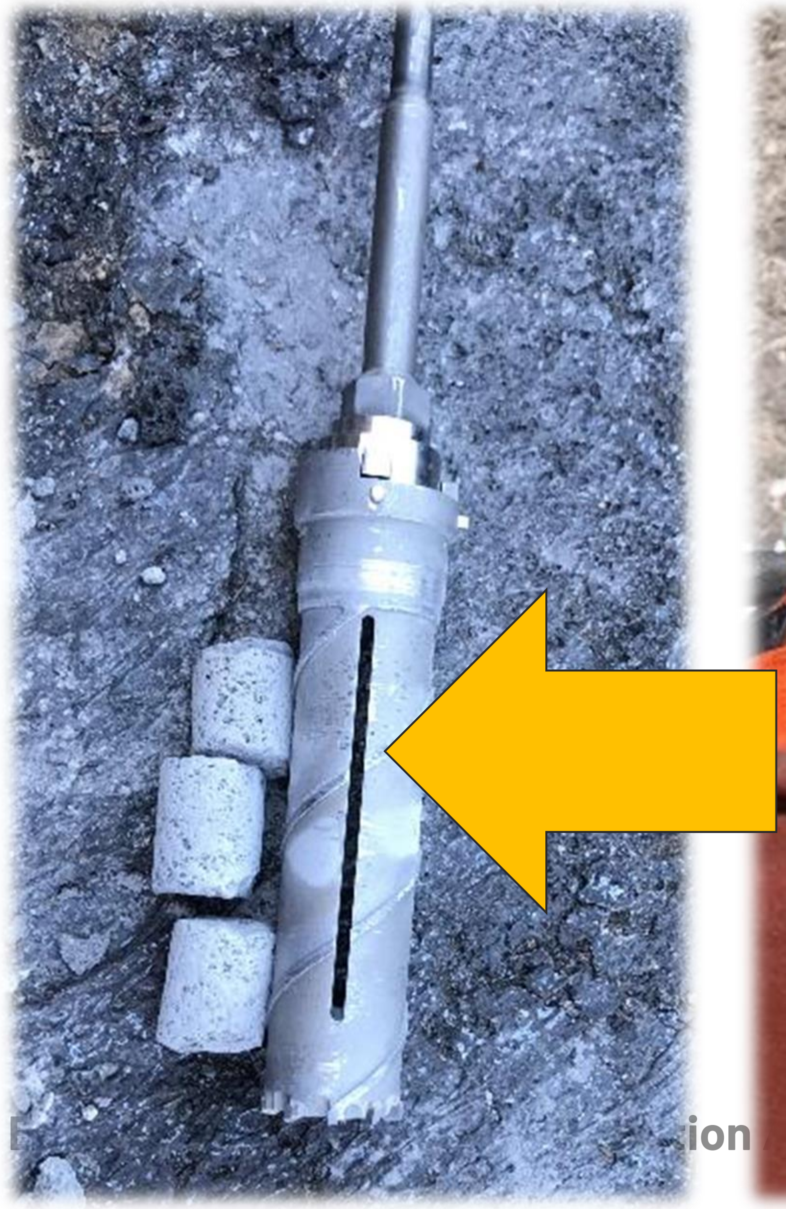
Ensure that the sample removal window is oriented vertically

Remove exterior auger to expose sample

Atacama, Arizona, Hawaii

- 5-10 min per 10 cm long core in hard basalt
- The large cutout in breakoff tube allows easy core removal. Solves a lot of core handling issues.





Dumont Dunes

- Rented spacesuit props for documentary shoot
- Not a spacesuit but sufficient to make it harder to see and do things
- Performed numerous sampling/drilling/instrument deployment activities
- It’s a hard work.



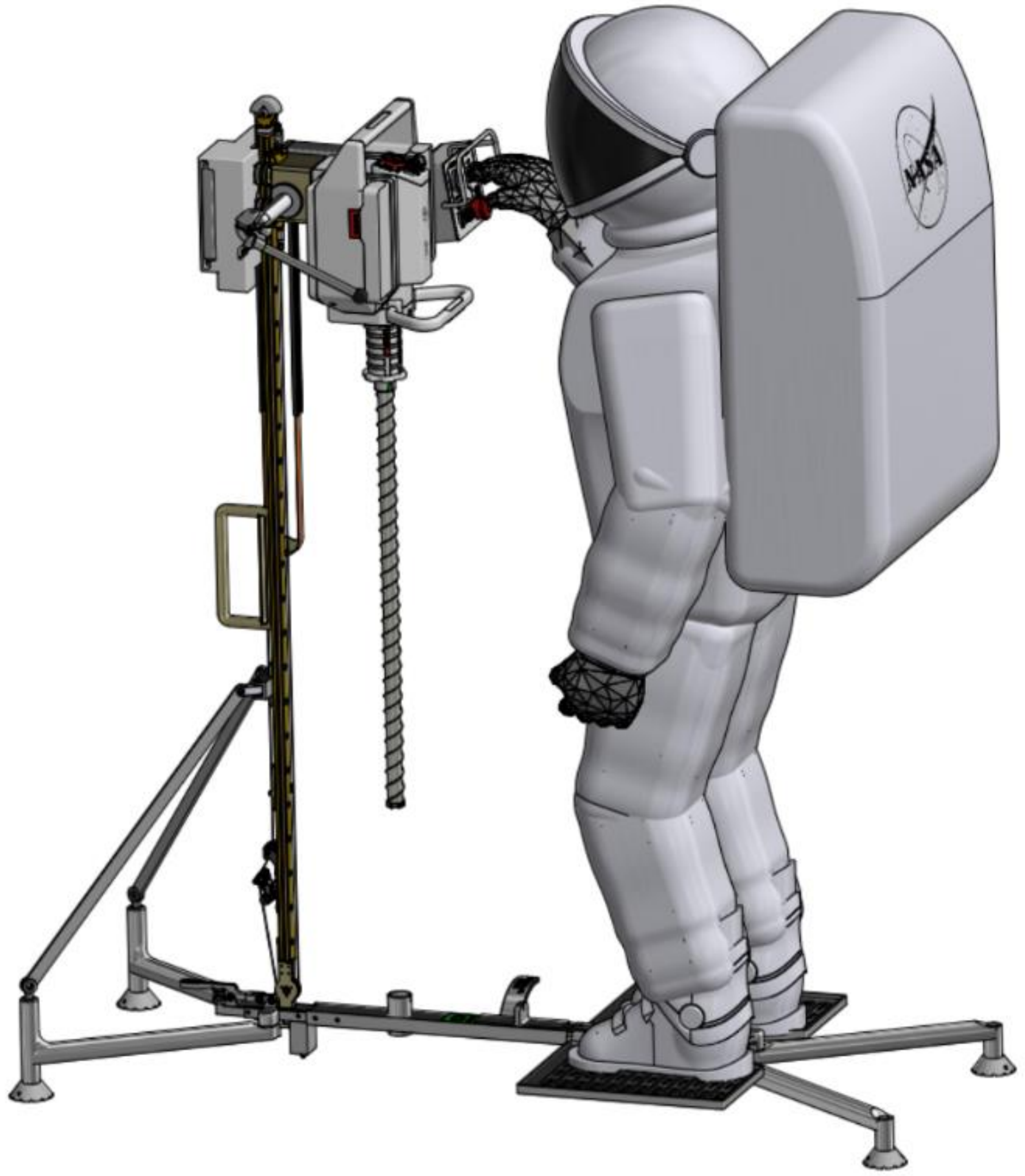

WHAT WOULD ARTEMIS SYSTEM LOOK LIKE?

Artemis Surface Drill + Container

- Combined lessons from Apollo, field deployments, and Artemis requirements
- Performed numerous design trades to produce optimal approach

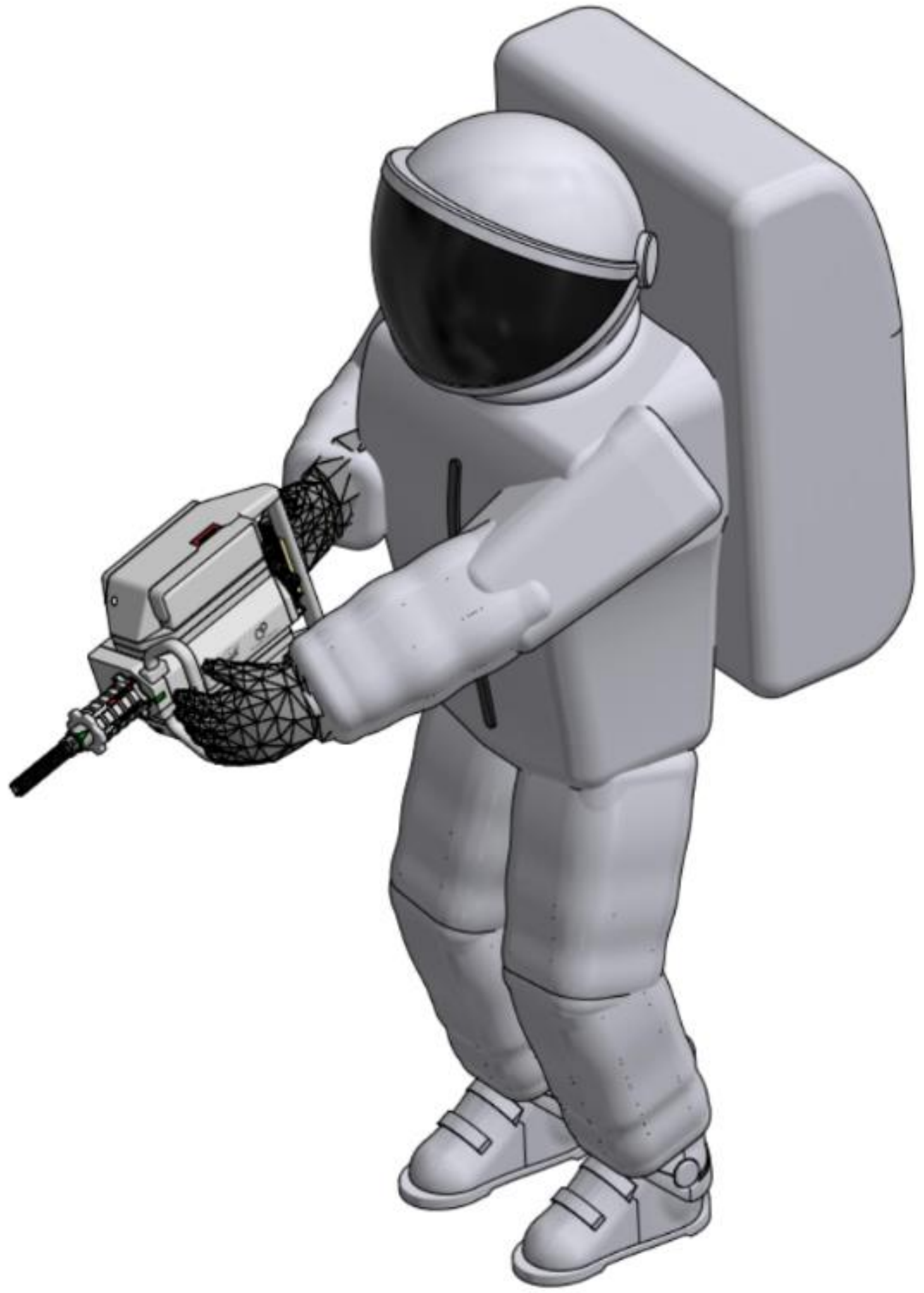
Deployed Configuration

- *3m Regolith Deep Drilling*
- *Static Cone Penetrometer*
- *Shear Vane*



Handheld Configuration

- *Surface Rock Coring*
- *1 m Regolith Deep Drilling*
- *Fastener Torquing*



Vacuum Sealed Container

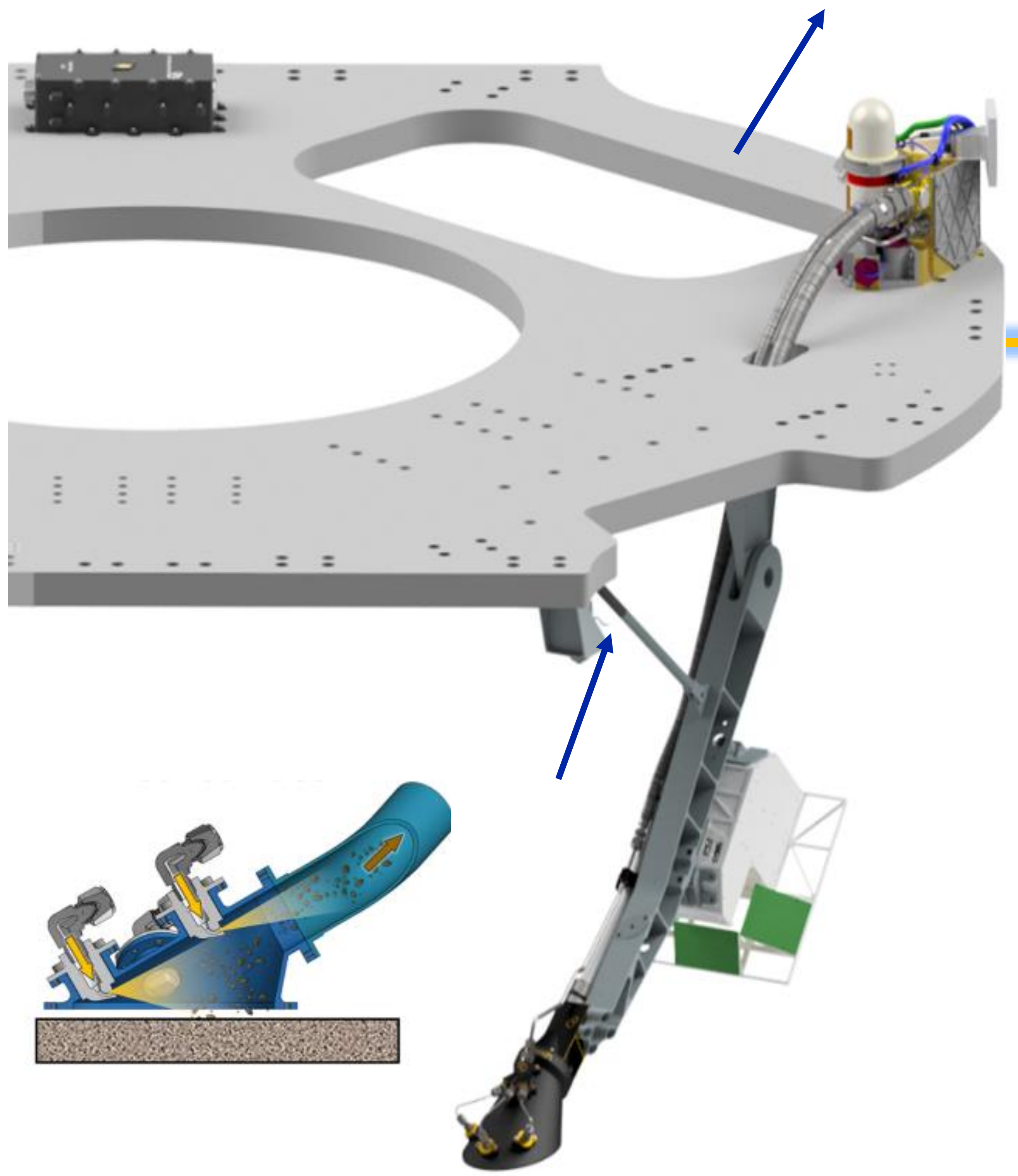
- *Regolith core*
- *Drive tube*
- *Preserves volatiles*

WHAT WE LEARNED FROM:

RECENT ROBOTIC MISSIONS

PlanetVac

PlanetVac jets N2 gas into regolith and lofts it into a sample container in seconds.



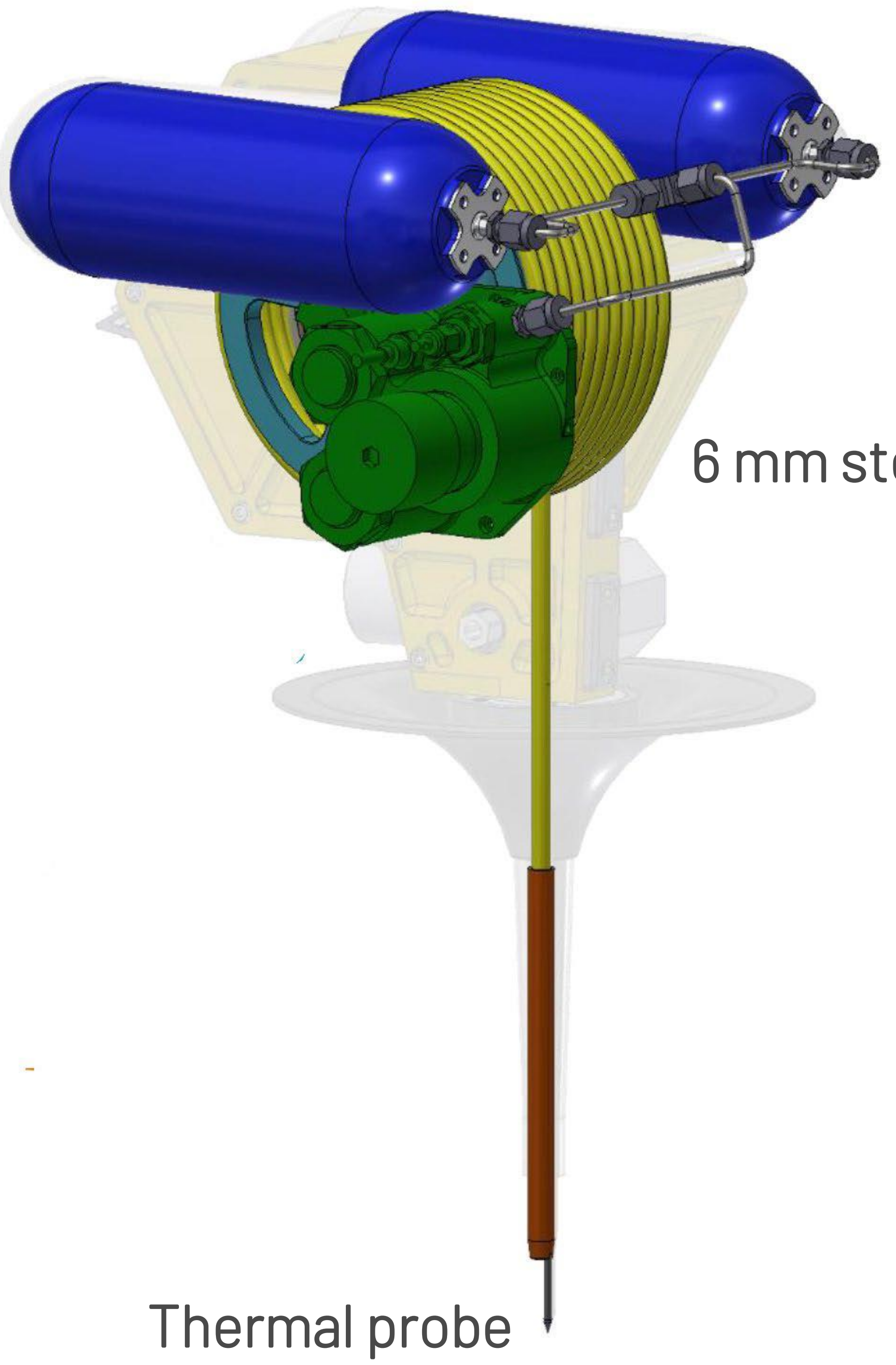
Compressed gas mobilizes and lots regolith up the transfer tube

Firefly Blue Ghost Lander

Launch: Jan 15, 2025
Landing: March 2, 2025
Location: Mare Crisium

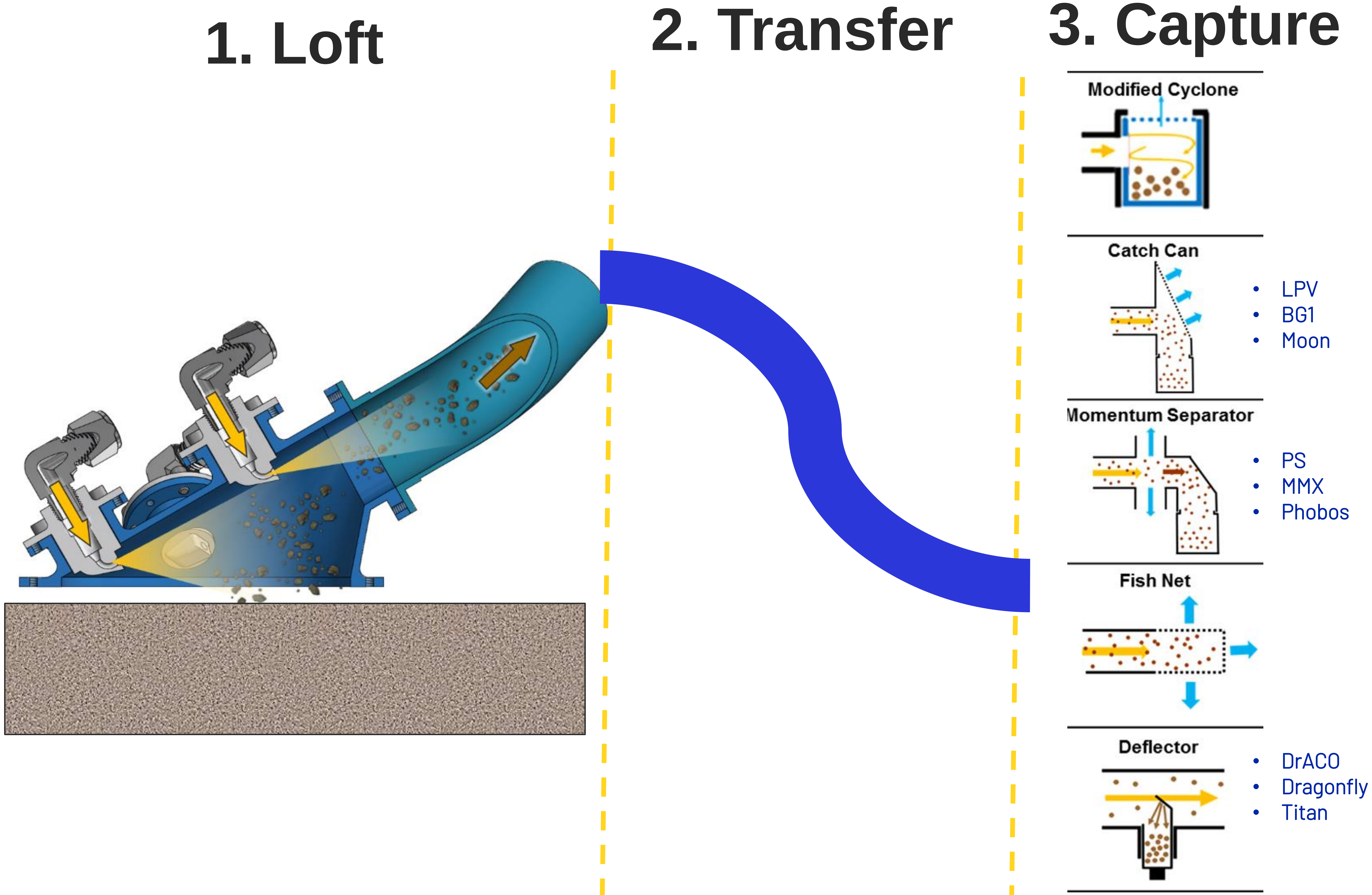
LISTER

LISTER uses 6 mm steel tube that spools out of the drum (like a garden hose), and drills into regolith using high pressure gas. Thermal probe measure temperature and conductivity.



PlanetVac Background

- How this works:
  - Gas sweeps (loft) surface material
  - In vacuum, gas is like an explosive making pneumatic systems very efficient
- TRL
  - Uses cold gas propulsion components: tanks, valves – TRL 9
  - Sampling head and delivery is mission dependent TRL6-9
- Benefits:
  - Simple operation (actuator opens valve)
  - Short sampling time
  - No ground-in-the-loop needed
  - Gravity agnostic
  - Sample delivery location independent from sample acquisition location



PlanetVac Operation

https://youtu.be/5KP2moq3SeA?si=cLlp375GjKR1clCy

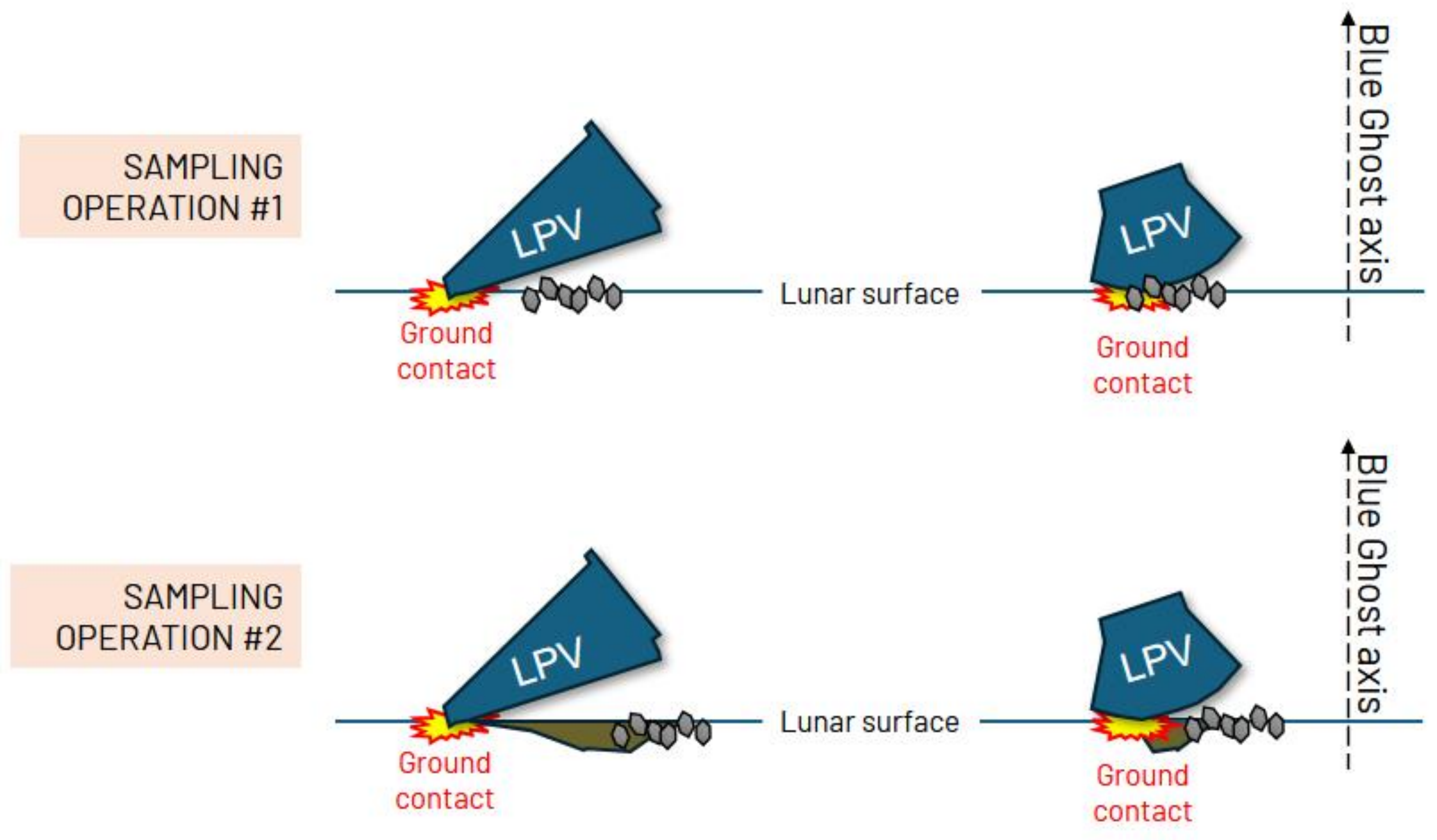
PlanetVac on the Moon

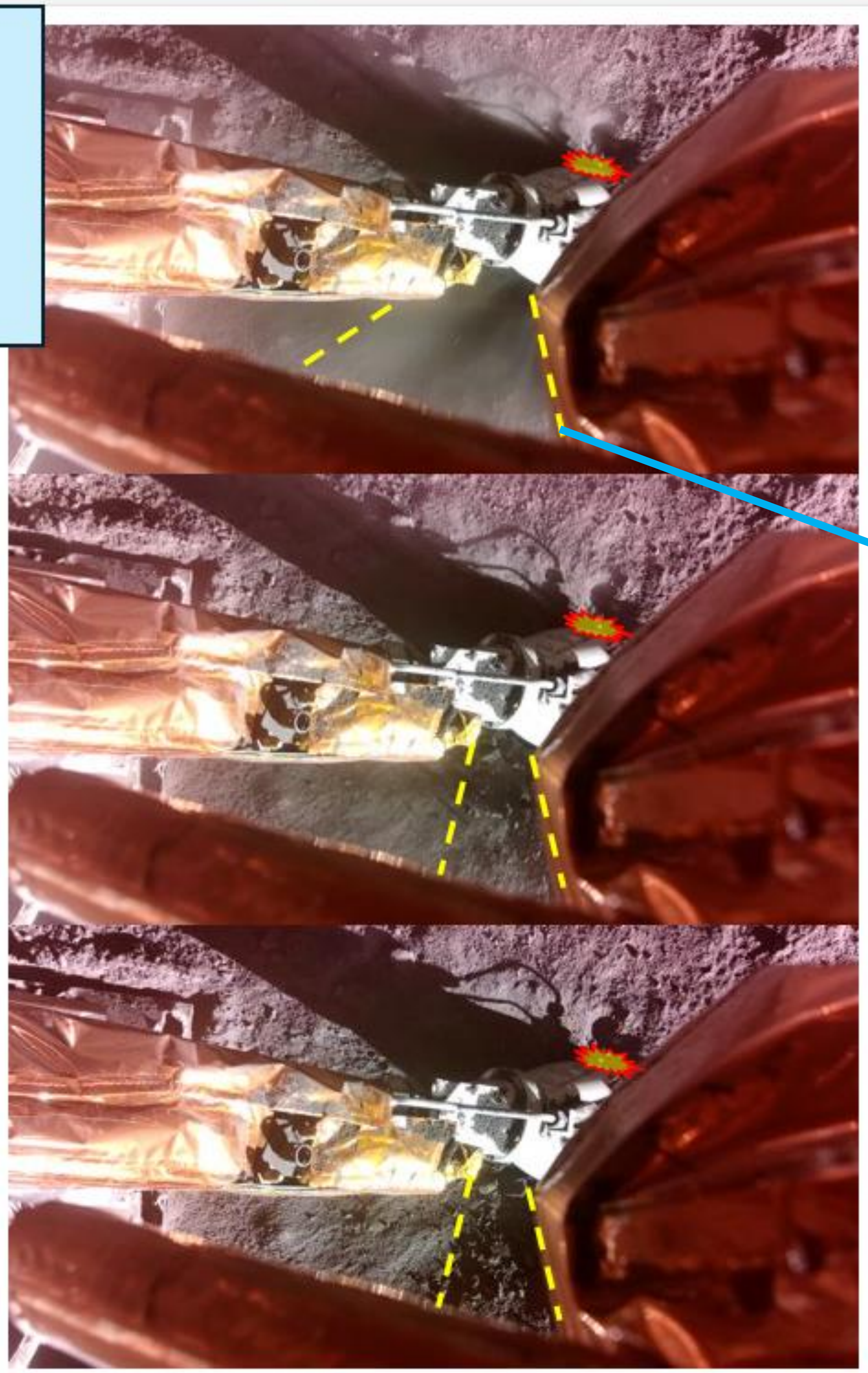
https://youtu.be/Di6WBa1w6H0?si=7zRSZ5ocjHvg1l9h

PlanetVac deployment

LPV is likely contacting the lunar surface only on its front edge on the sampling head. This results in both a pitch and roll case of the sampling head, which impacts LPV's capability in rock size collected.

Subsequent sampling operations will create a less favorable surface condition for sampling performance.



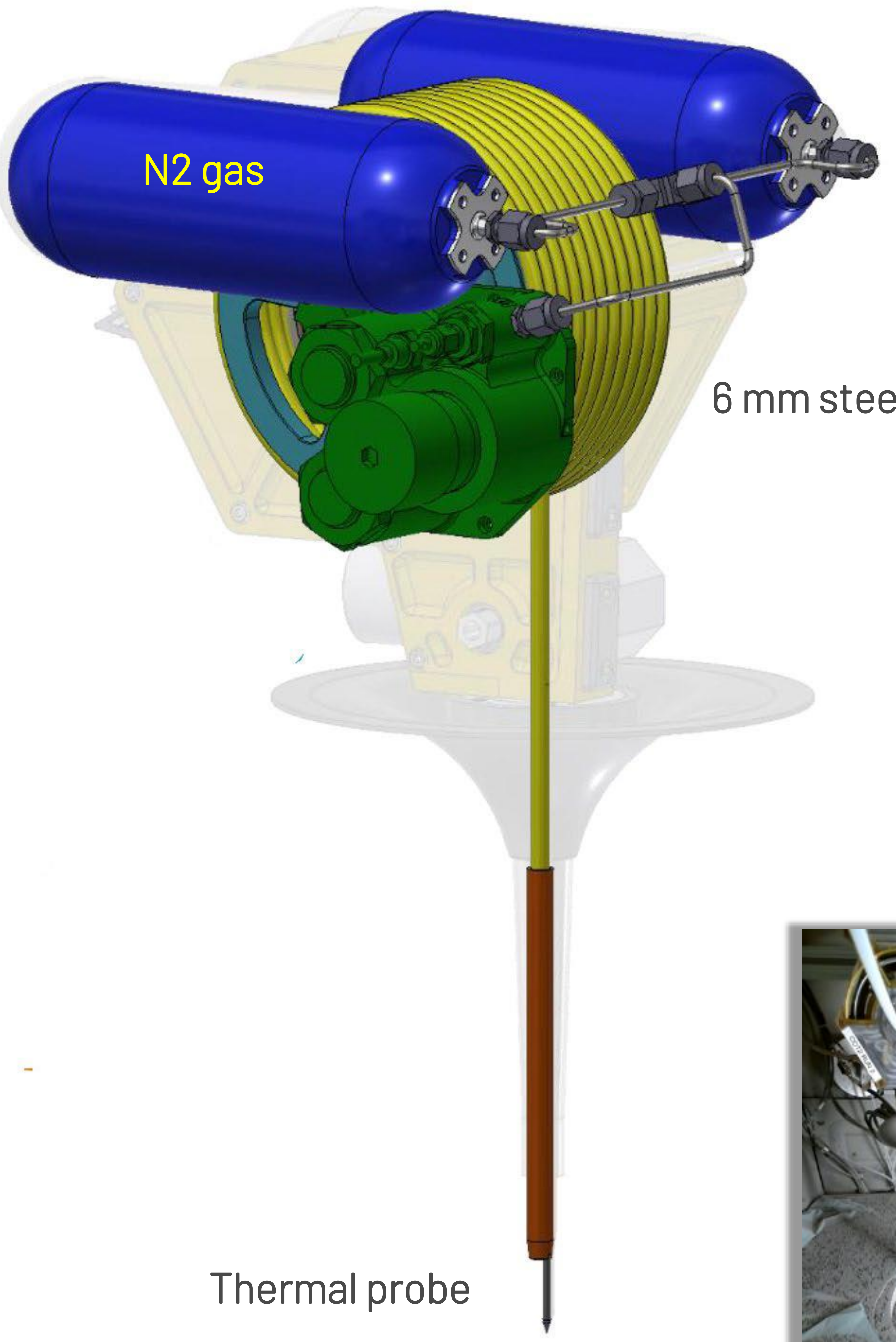


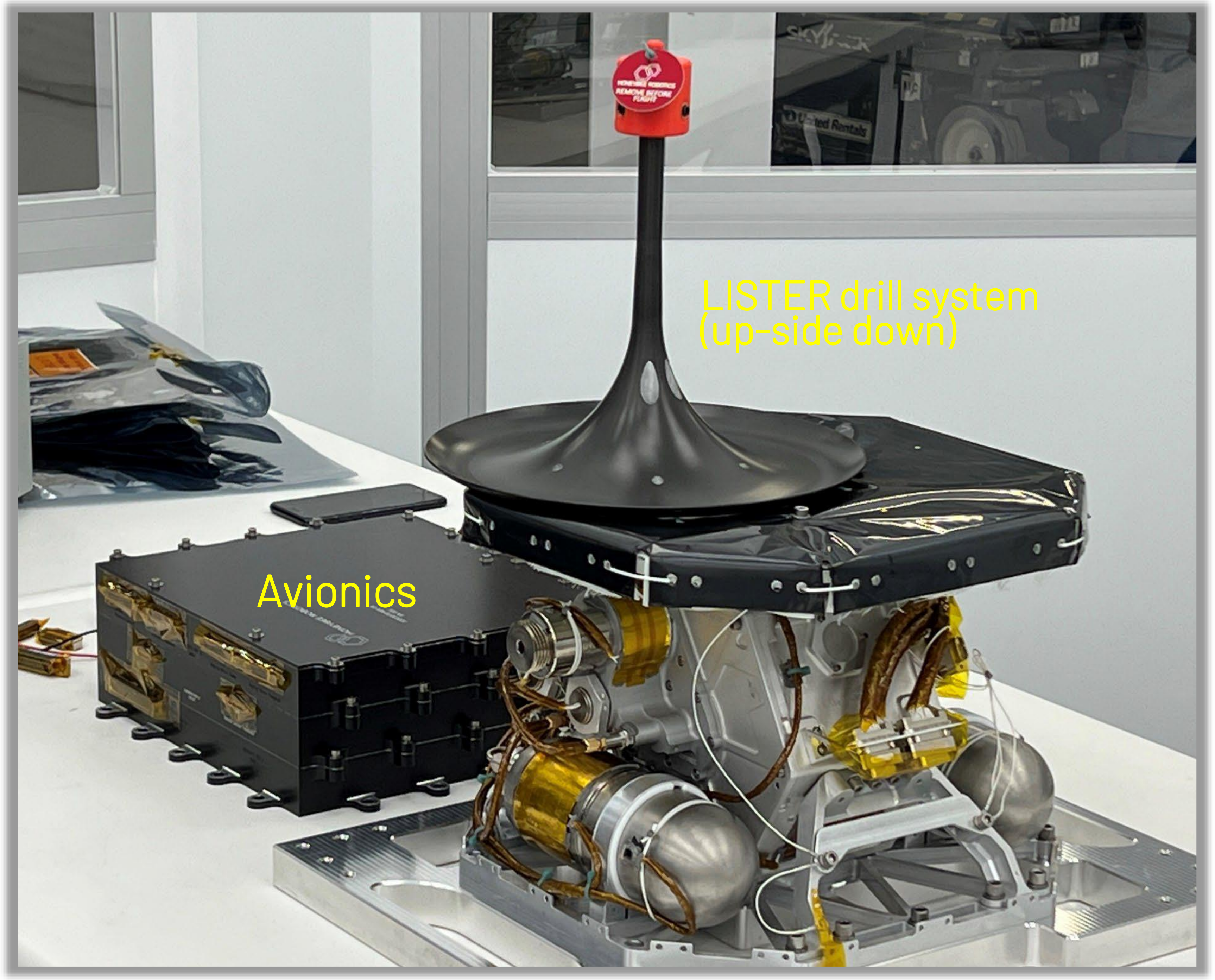
PlanetVac still managed to capture samples even in off-nominal deployment scenario

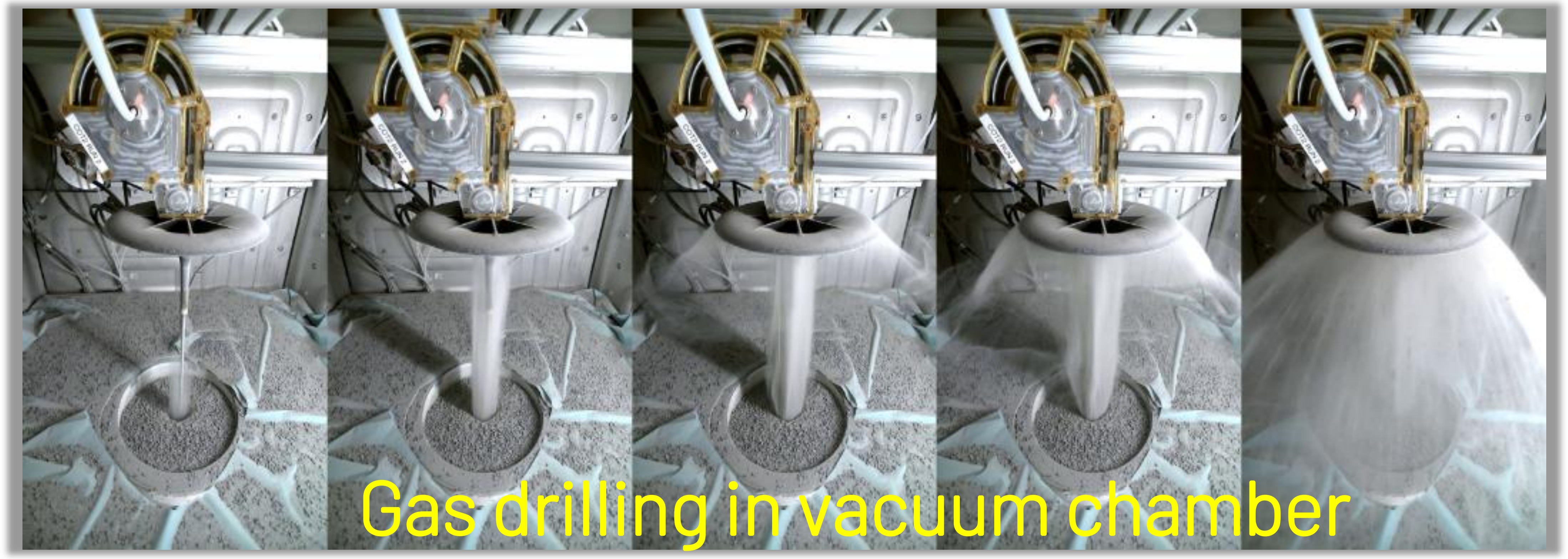
PlanetVac Sampling and Sieving

LISTER Pneumatic Drill and Thermal Probe

- LISTER uses 6 mm steel tube that spools out of the drum (like a garden hose), and drills into regolith using high pressure gas.
- The 6 mm tube is used as conduit for gas and wires for thermal probe.
- LISTER is designed to drill to 3 m depth in minutes and measure temperature and thermal conductivity.
- Mass: 13 kg, incl. avionics
- Power: 60 Watts
- LISTER can be scaled up to drill to 10 m depth with addition of downhole motors and drill bit.
- LISTER was the first pneumatic drill on the Moon.







LISTER Operation

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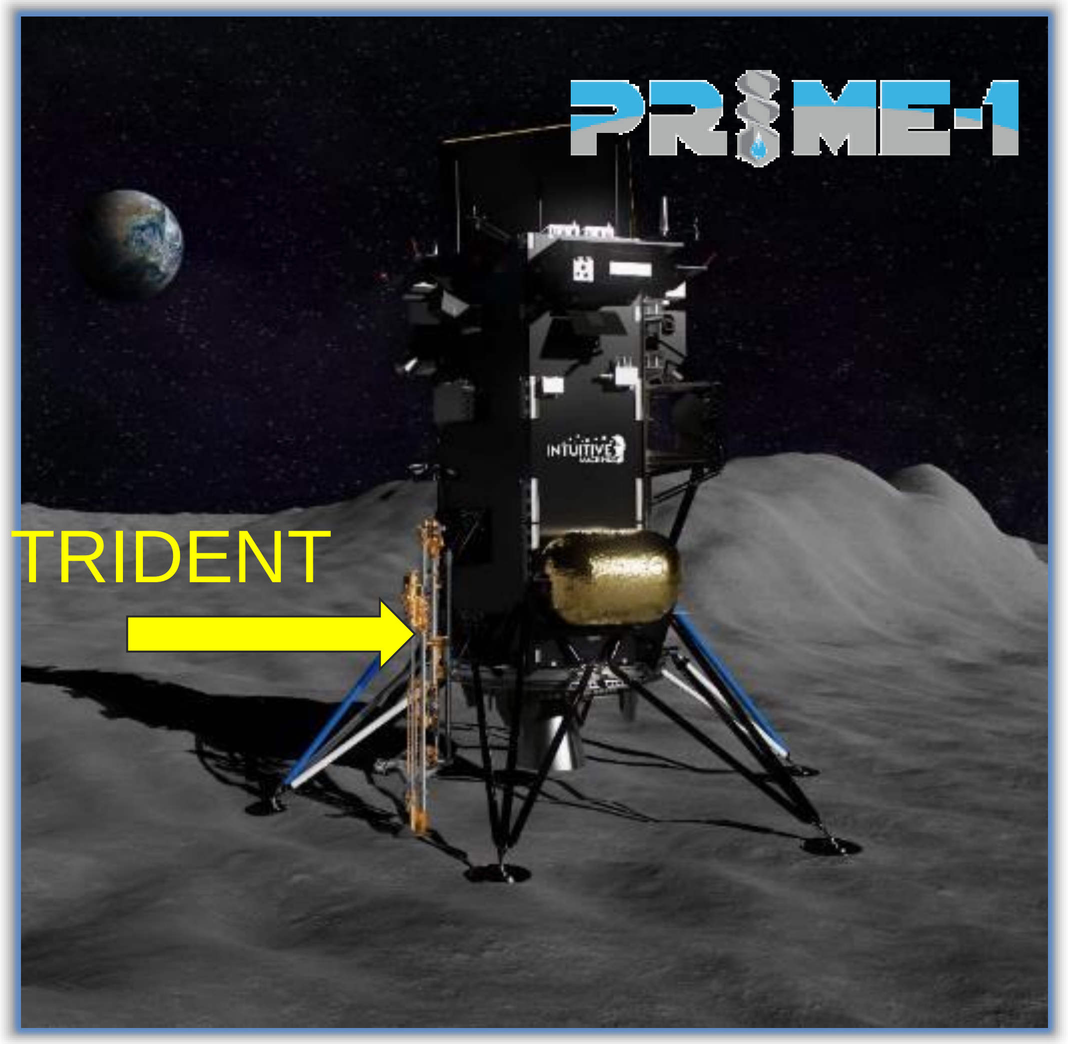
LISTER on the Moon

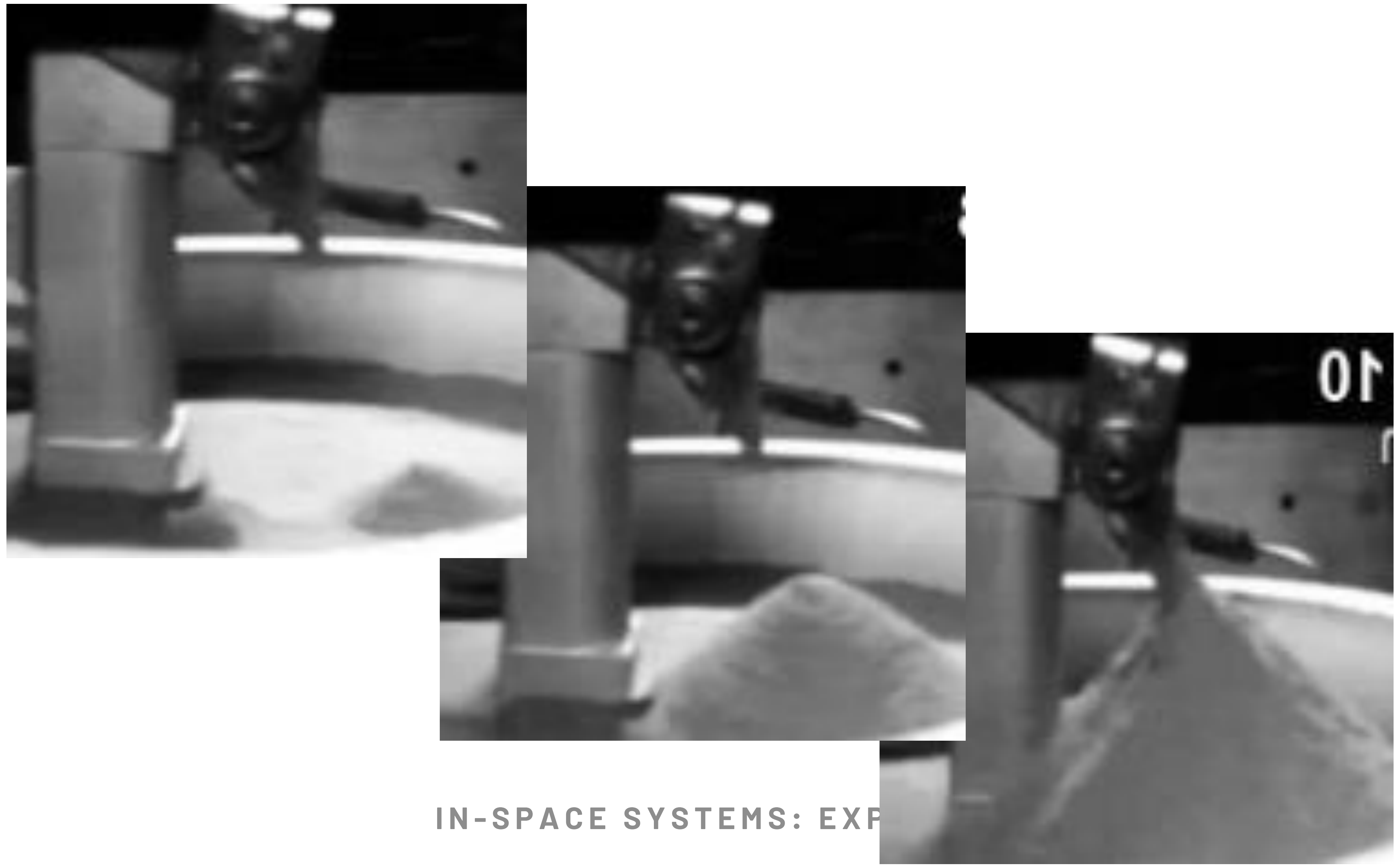
https://youtu.be/sgQLmh6FpoU?si=dvVbeTLJtMsk2sbn

TRIDENT drill

https://youtu.be/YVgMvApKo6w?si=YAuQ7Bn7qmSI80qC

- TRIDENT is a 1 m hammer drill designed for hard rocks and ice rich regolith
- TRIDENT has drill integrated heater and 2 temperature sensors
- TRIDENT mass is 25 kg., incl avionics
- TRIDENT life: 50 holes (depending on material strength)
- TRIDENT was successfully operated on the Moon as part of the IM2 mission
- TRIDENT is also integrated into VIPER rover



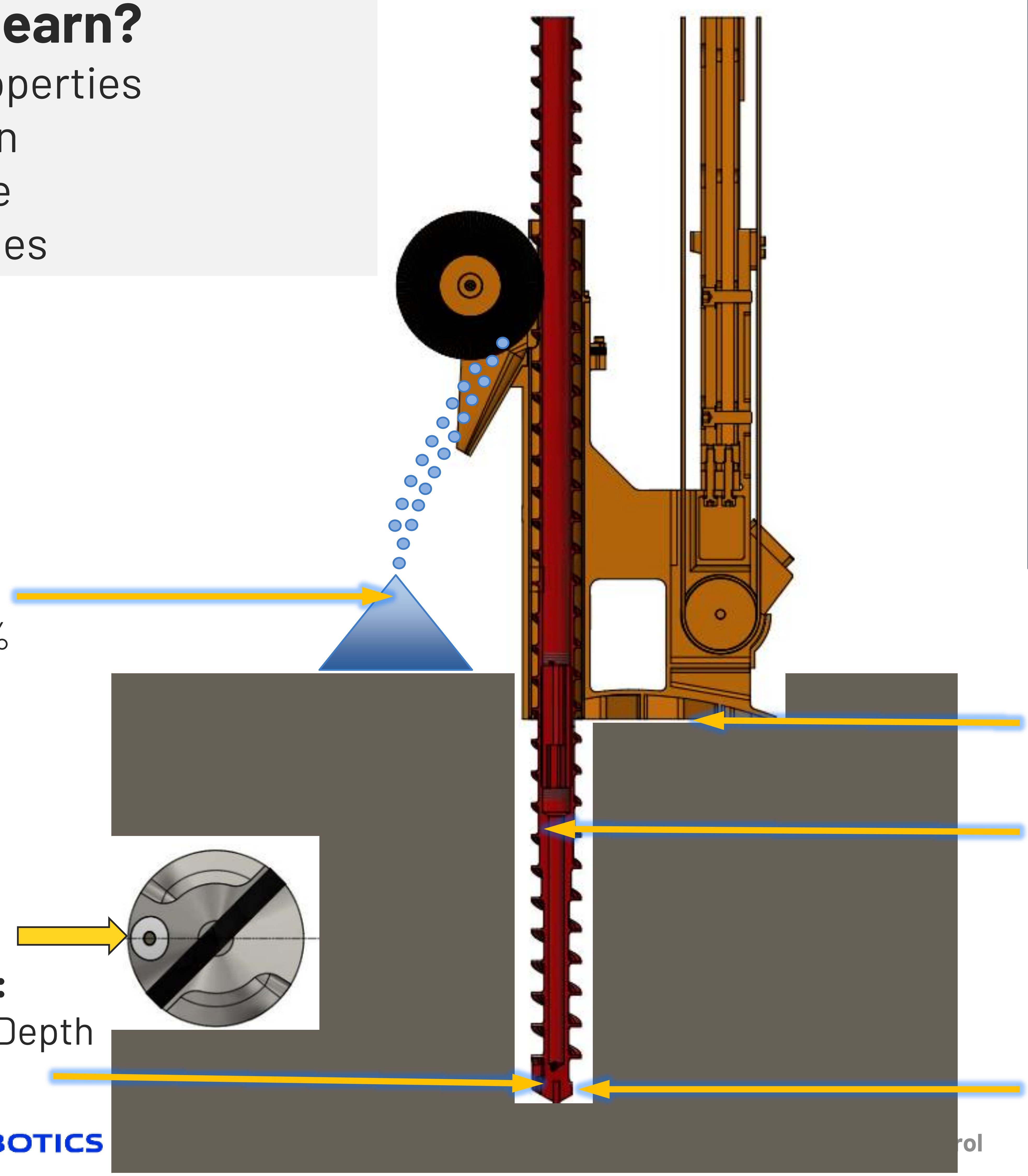


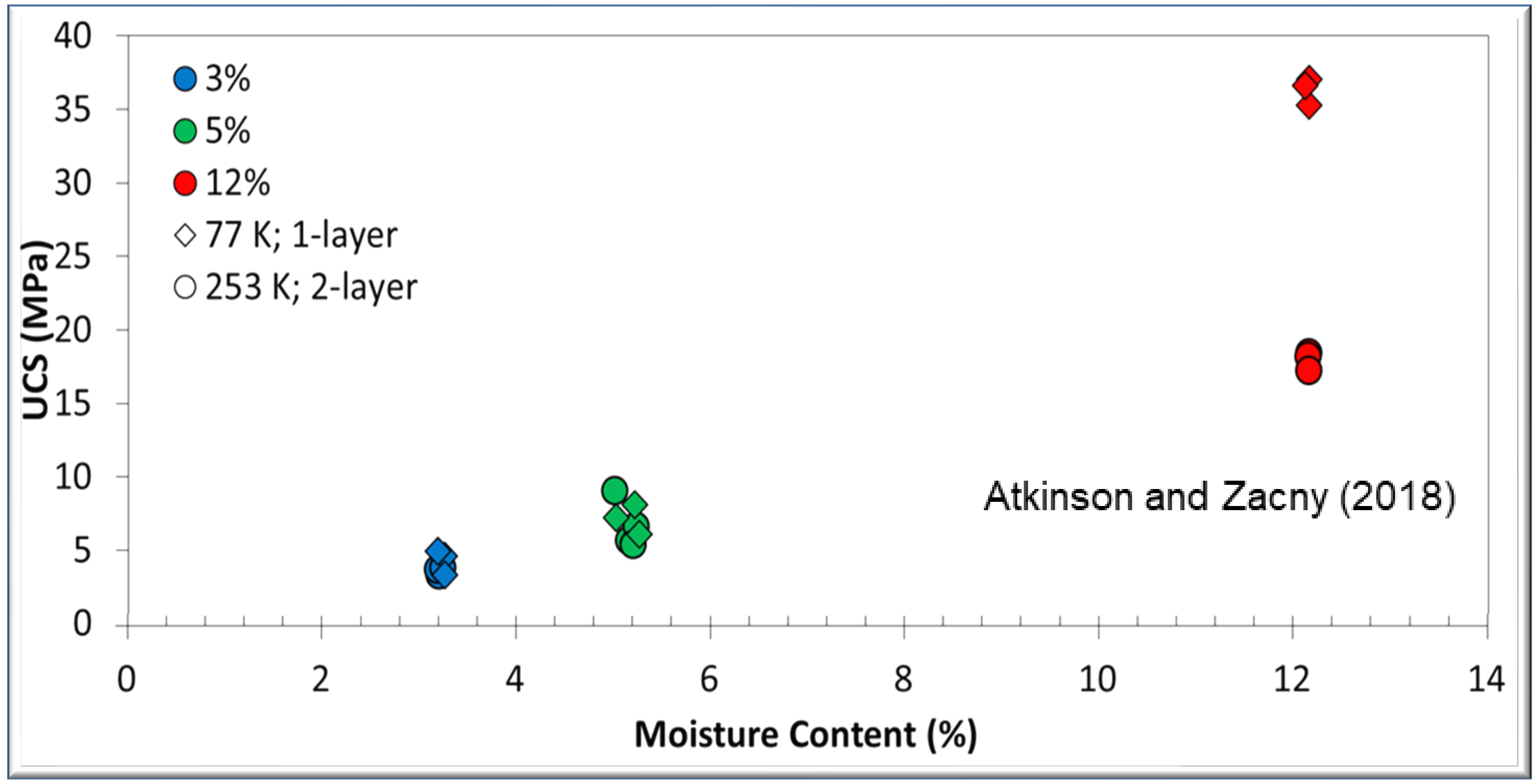
Science Data from TRIDENT drill

What could we learn?
- Geotechnical properties
- Ice concentration
- Ice physical state
- Thermal properties

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

Bit Temperature Sensor:
- Subsurface Temp vs Depth





Footpad sinkage provides:
- Bearing capacity

Heater:
- Thermal Conductivity (with Temp. Sensor)

Drilling Power:
- Material Strength vs. Depth
- Water-ice concentration
- Loose ice grains vs ice cemented regolith

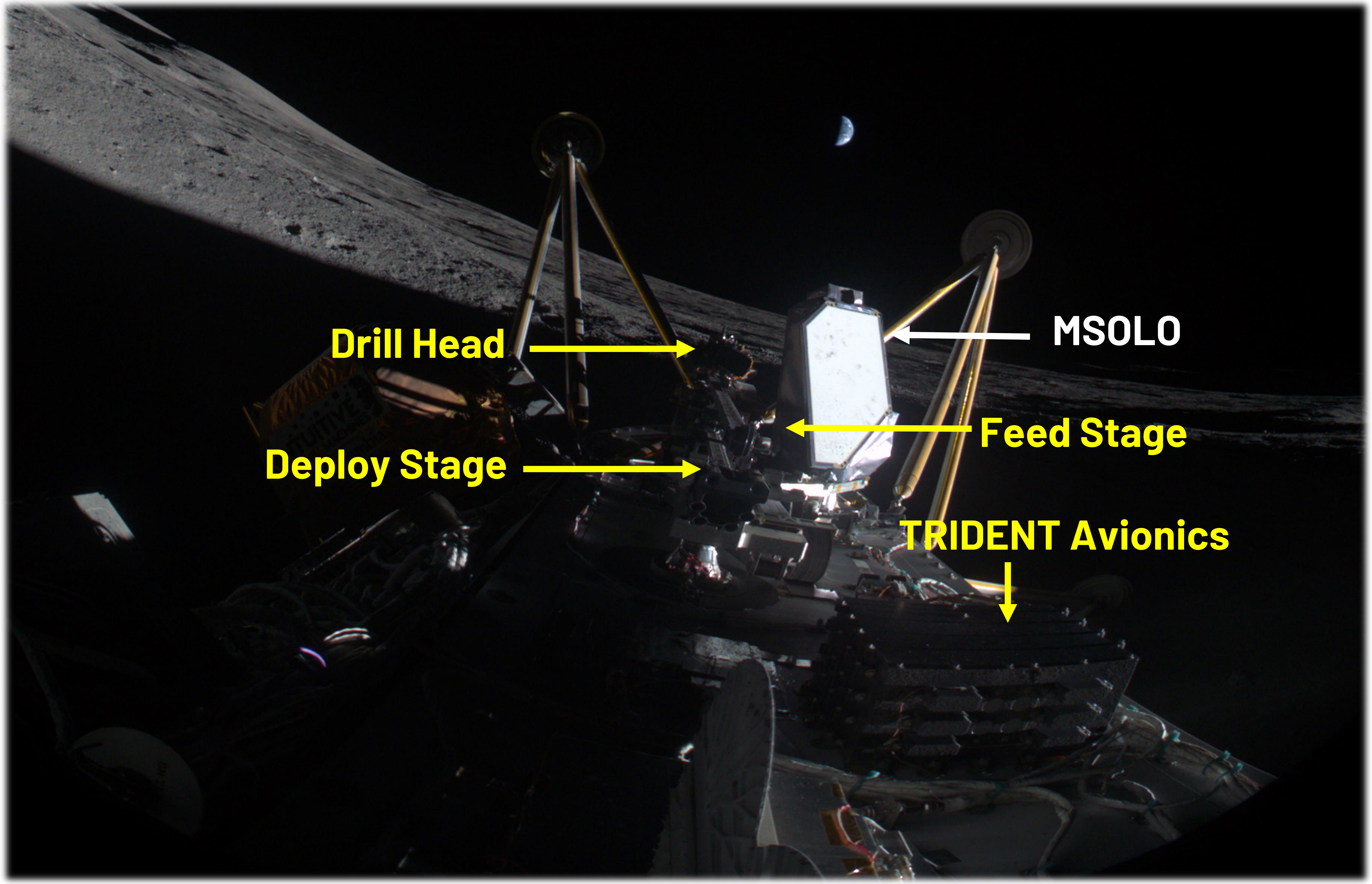
TRIDENT and MSOLO on the Moon

<u>In-Transit Check Out</u>

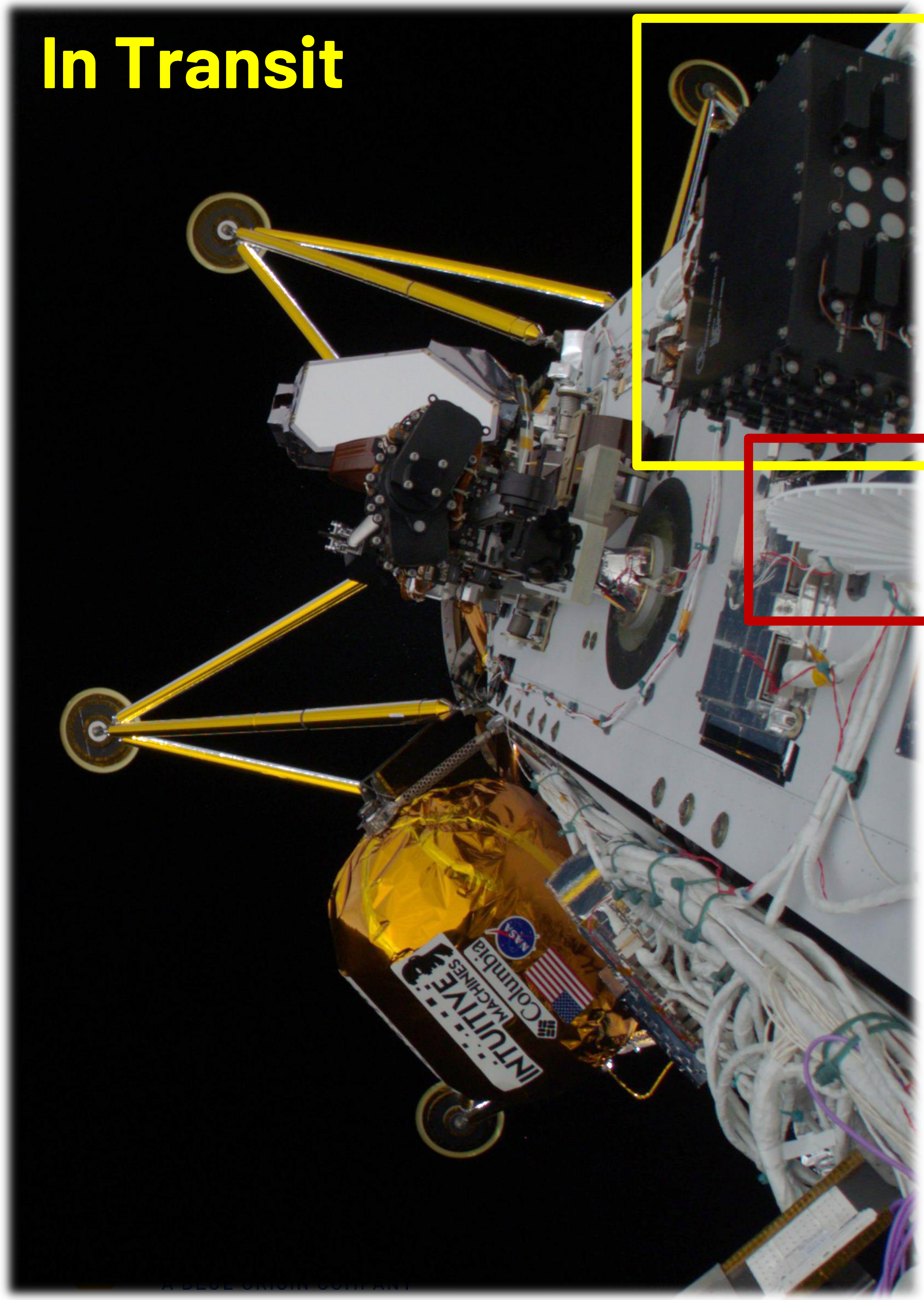
- Auger rotation
- Recorded thermal and avionics health data

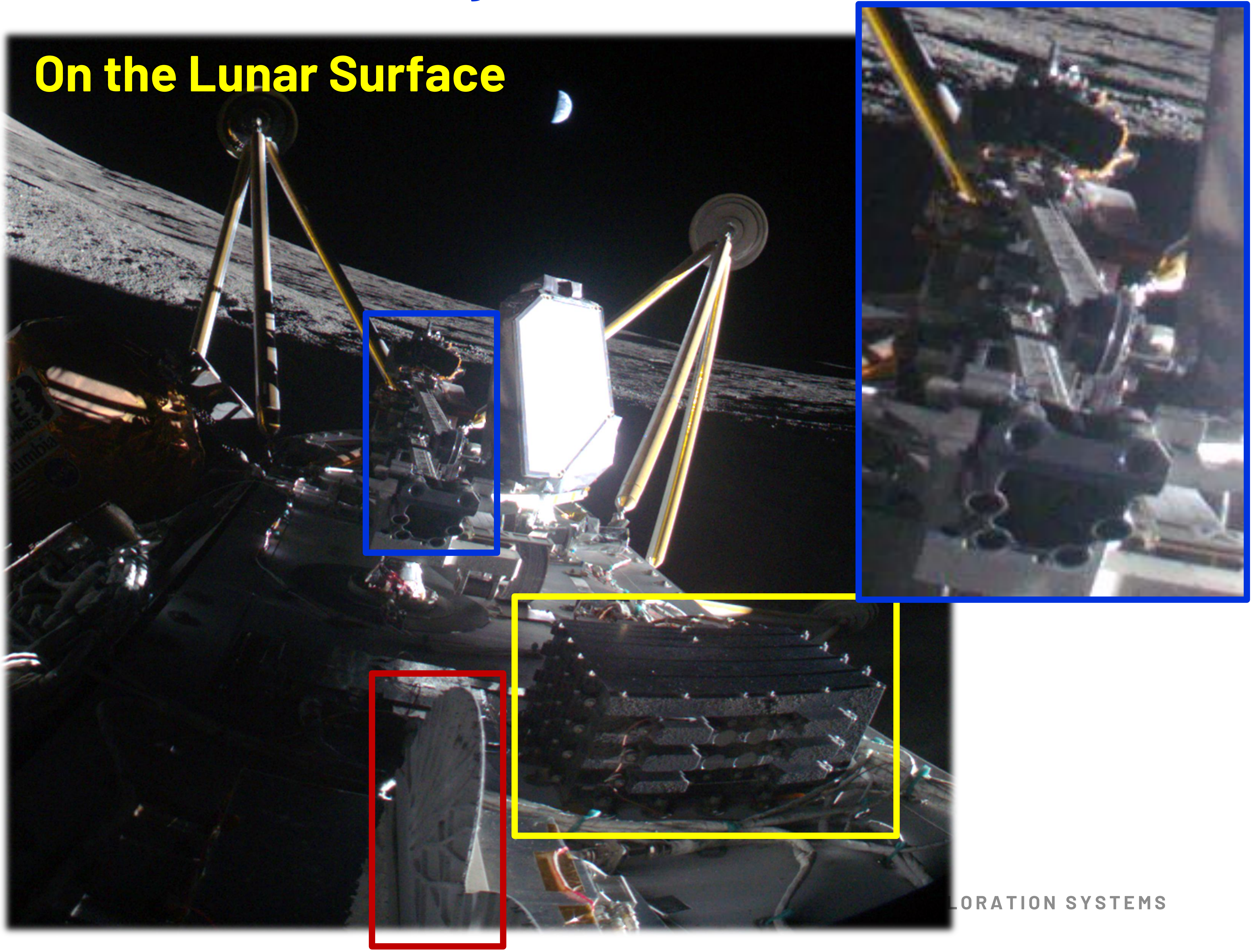
<u>Surface Operations</u>

- Auger rotation
- Auger percussion
- Released launch locks
- Deployed to 'surface'
- 'Drilled' to 1 meter depth
- Cycled heater in drill bit
- Recorded all thermal data



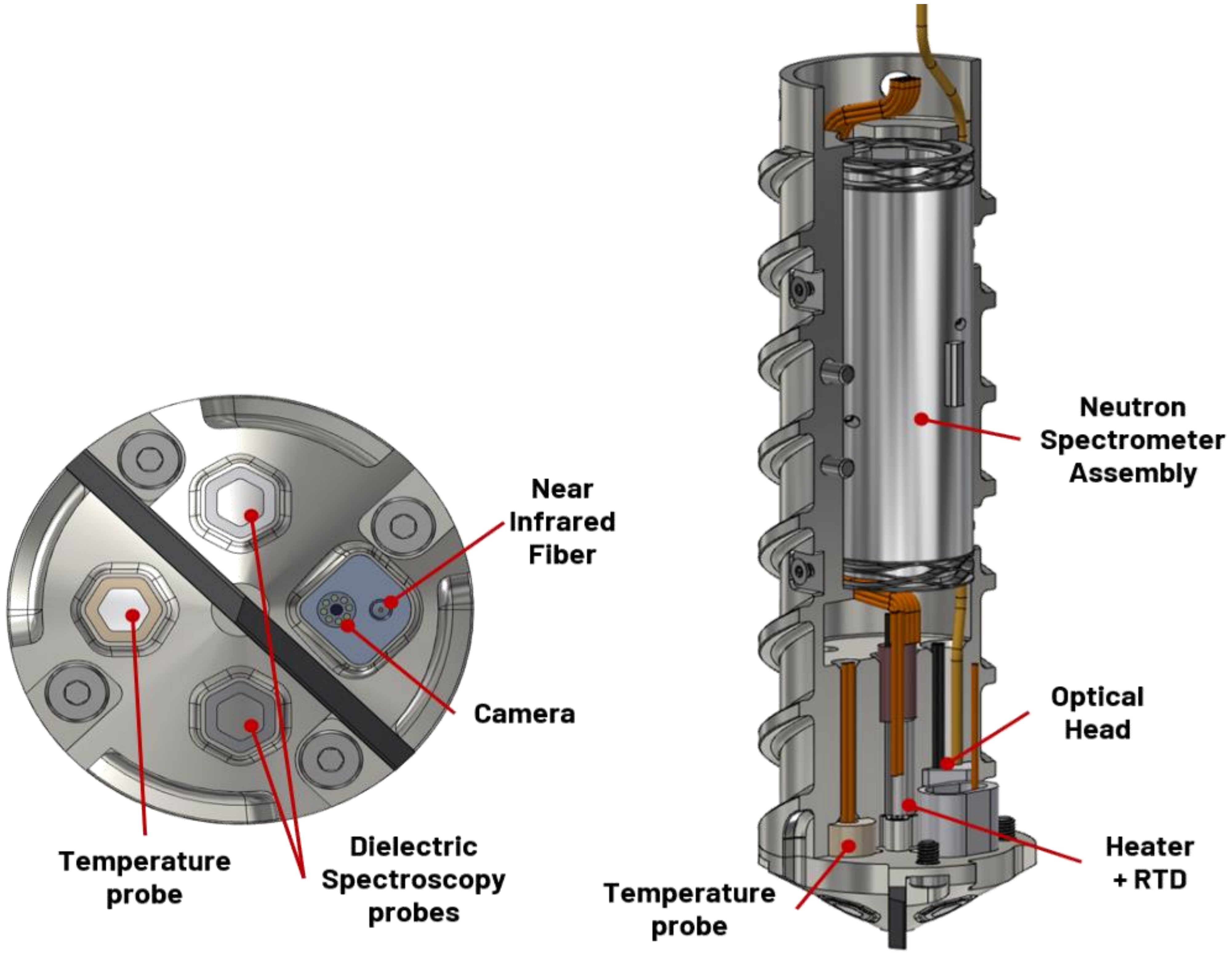
TRIDENT Operated in Dusty Environment



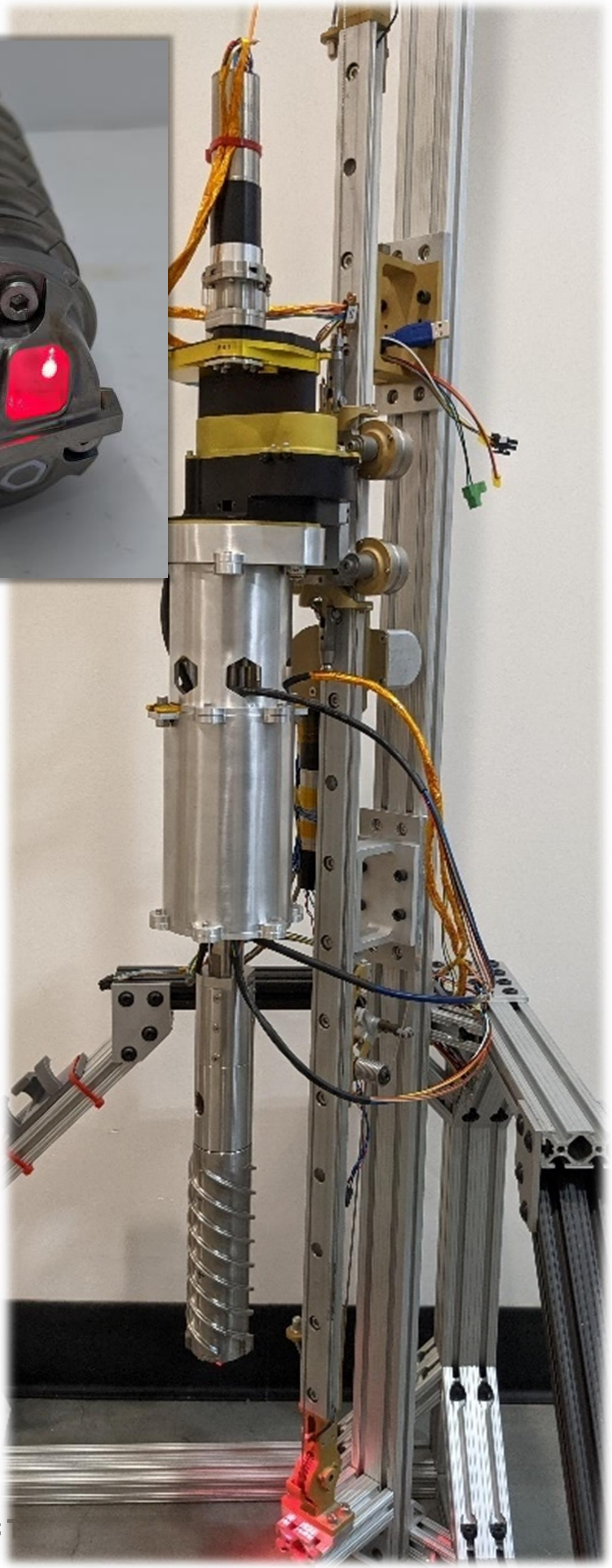


SMART TRIDENT

- SMART has integrated downhole instruments
- It brings instruments to a sample (as opposed to sample to an instrument)
- Allows true in-situ analysis
- Allows for stratigraphic analysis

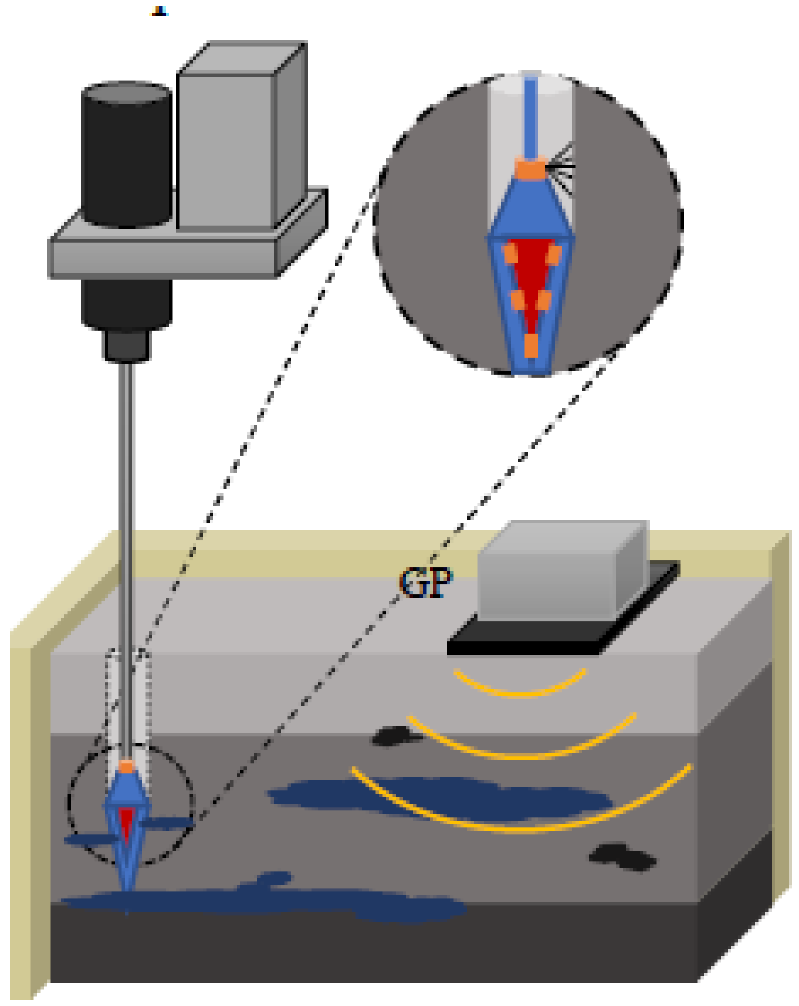


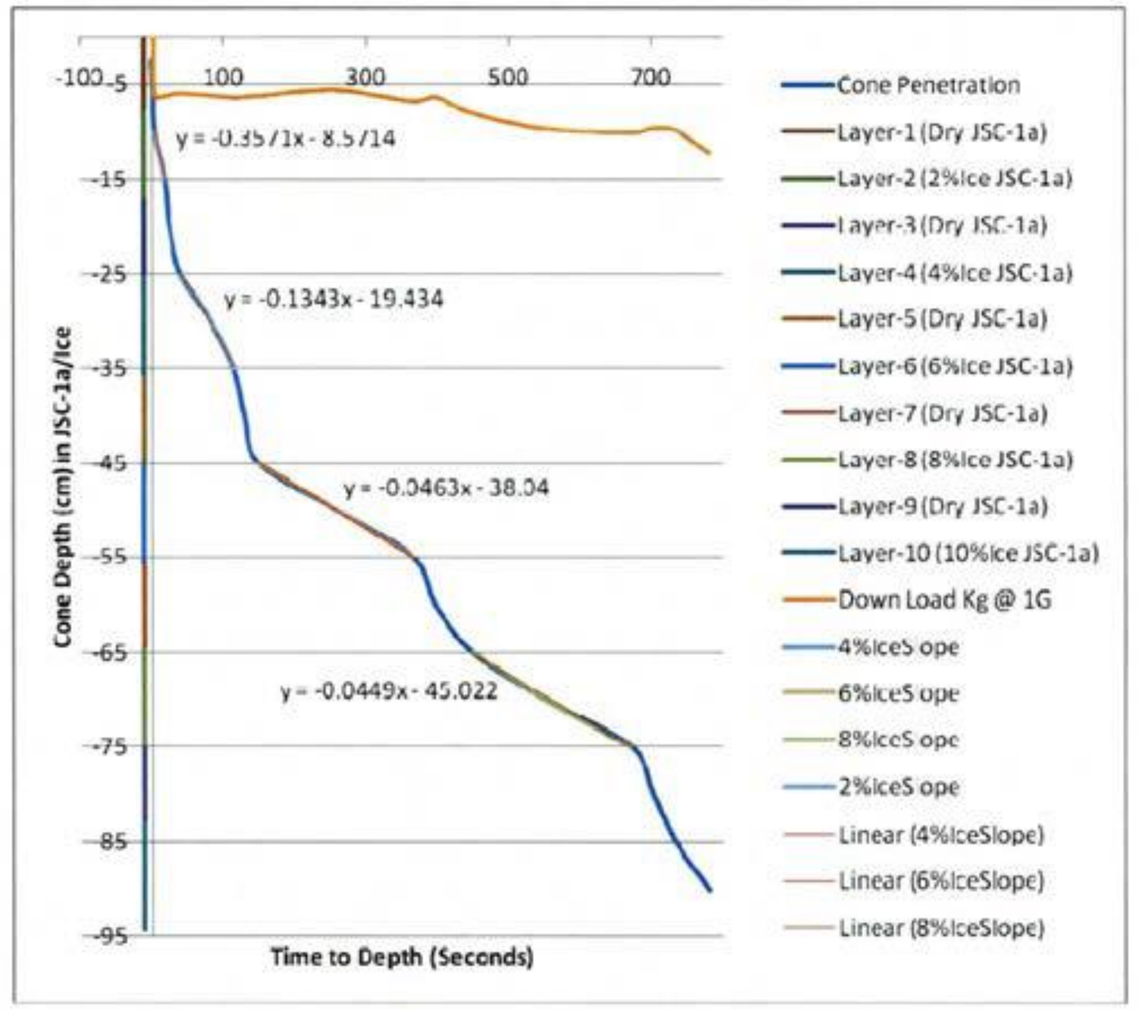
Devon island

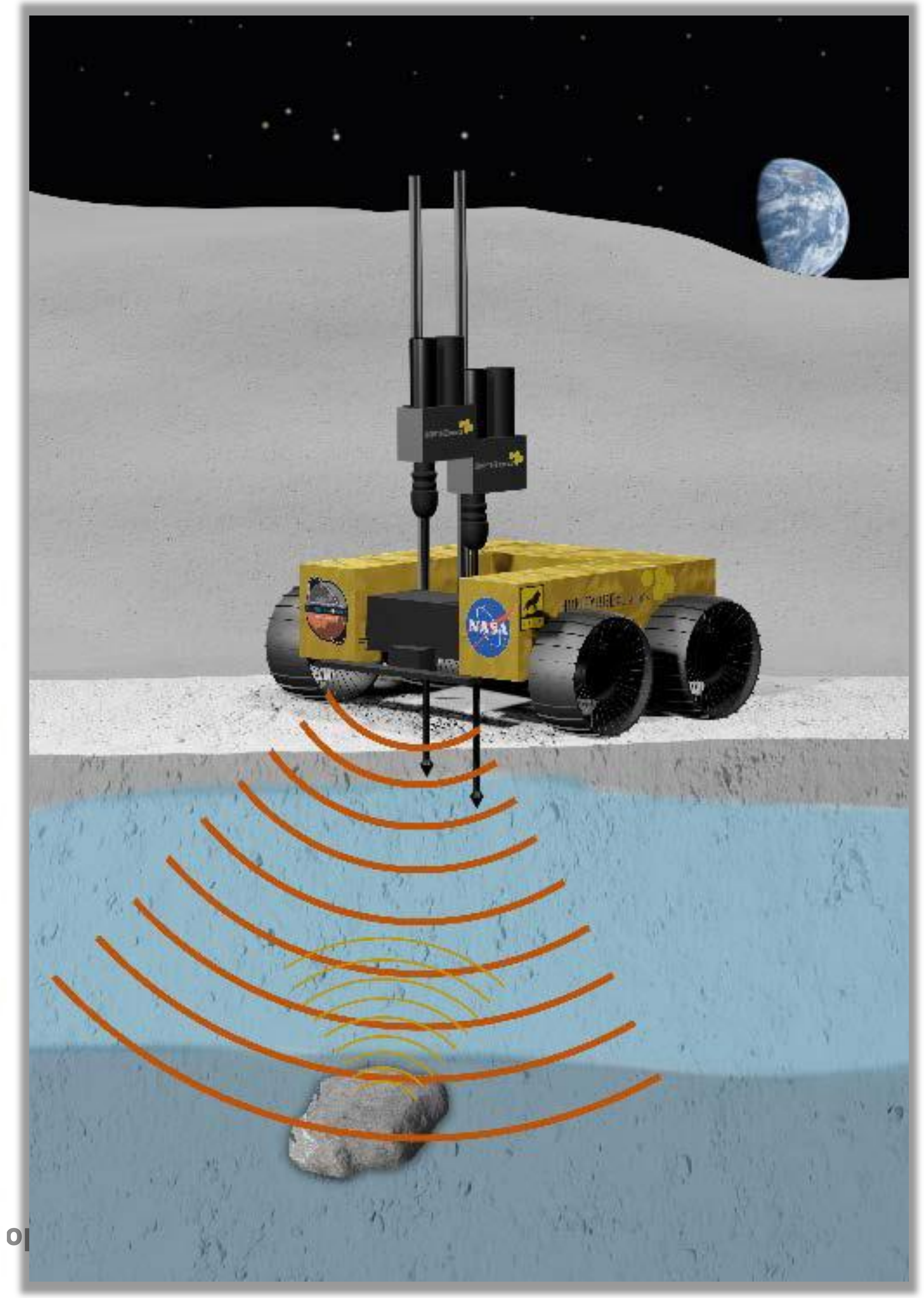


Percussive Hot Cone Penetrometer

- Combination of var geotechnical and geophysical measurements
- PI: Paul van Susante, Michigan Technological University (MTU)



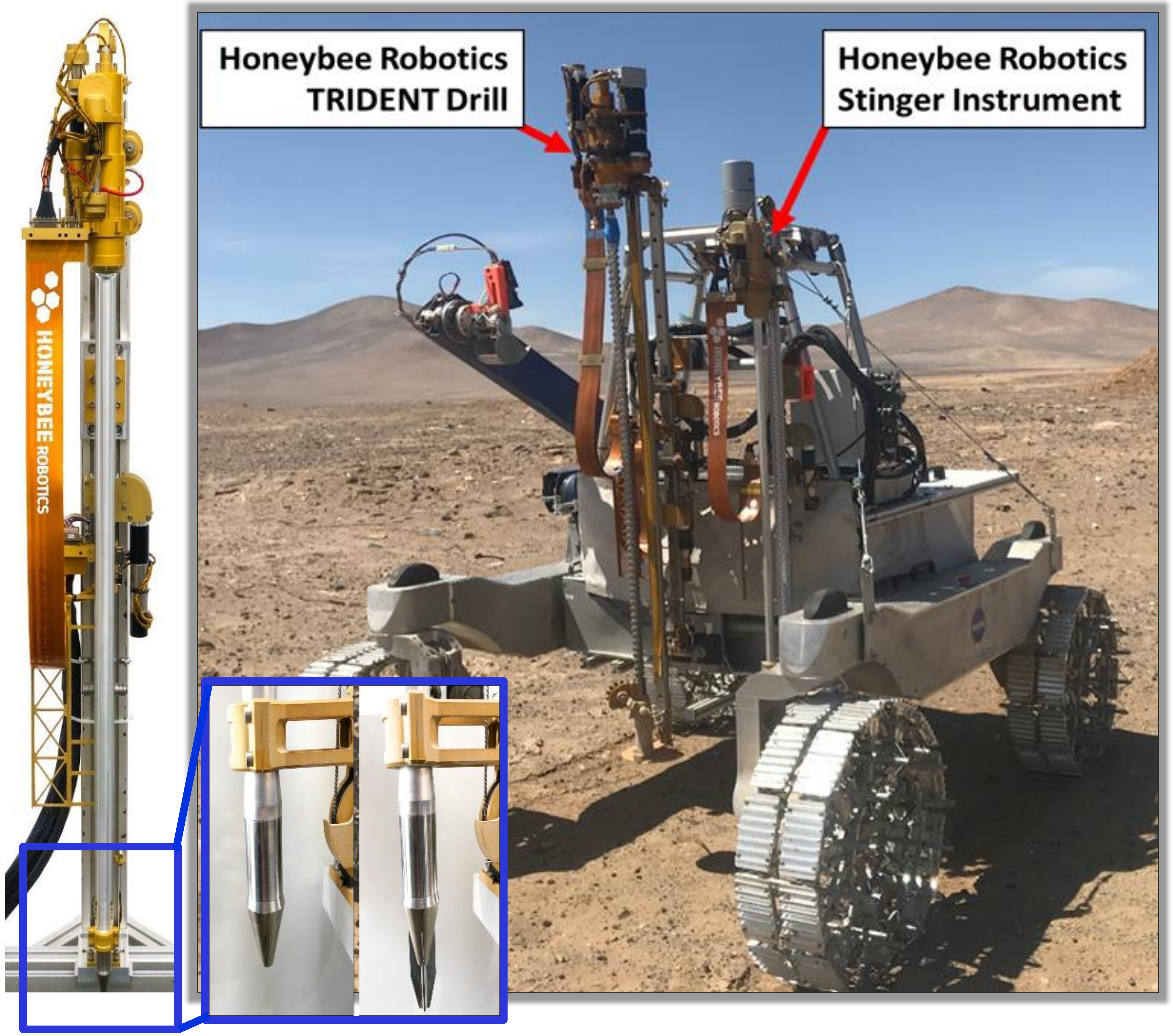




STINGER & SPARTA

- STINGER:
  - Rover or lander mounted geotechnical instrument
  - Measures shear strength and bearing strength of regolith
  - Depth: 50 cm (nominal) but could be 1 m
  - Could include downhole Temp, Heater, Instruments
  - Deployed in a lab and Atacama on KREX-2 rover

- SPARTA:
  - Rover or lander mounted geotechnical instrument
  - Measures shear strength and bearing strength of regolith
  - JPL & HBR development



Conclusions

- Working with regolith takes a lot of effort. Being inside a heavy spacesuit with little maneuverability makes it so much harder
- Activities such as deep drilling should be left for robotic systems or need to be mechanized (e.g., astronaut presses buttons and motors do the work)
- Activities such as getting a core from a large boulder could be done by astronauts with a handheld coring system
- There is no substitute for testing in lunar analog sites – even on a skinny budget
- Precursor robotic systems are critical part of crewed exploration. They provide critical reconnaissance and ground truthing + enable testing of new technologies

Thank you!