National Aeronautics and Space Administration

Key Differences in Operating a Rover on the Moon vs. Mars

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Spaceops Works Shop 2017

Academics, Practicality, Innovation

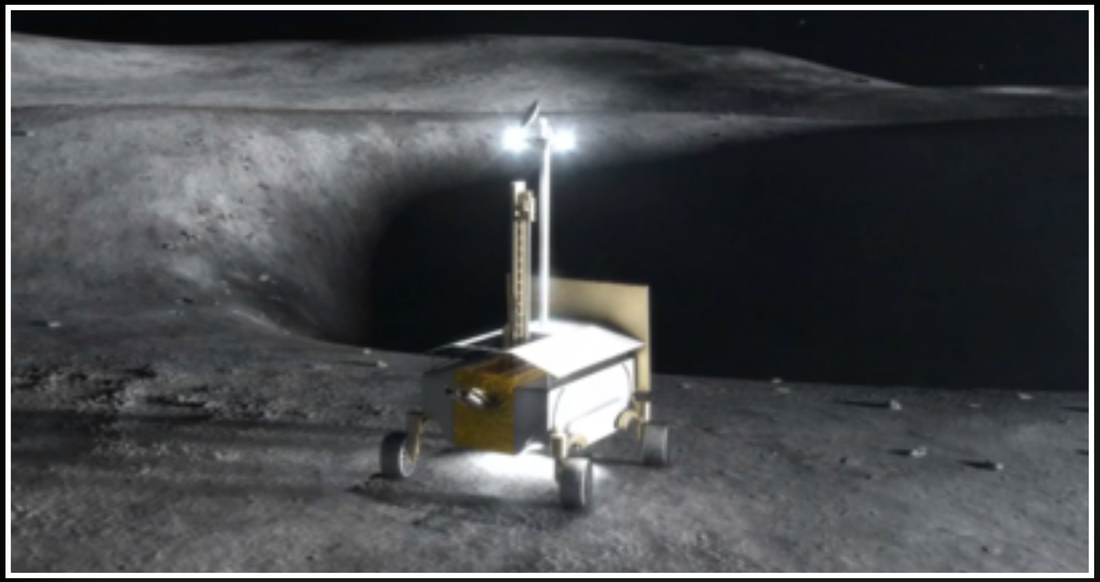
- Admiral Rickover distinguishes the academic from the practical, using a nuclear reactor as an example
    - Academic - in the study phase, low cost...
    - Practical - being built now, expensive, requires significant development resources on apparently trivial elements
- My notes
    - It's hard to innovate on a project focused only on the practical
    - The academic study can be fertile ground for new ideas that build the future and challenge current assumptions

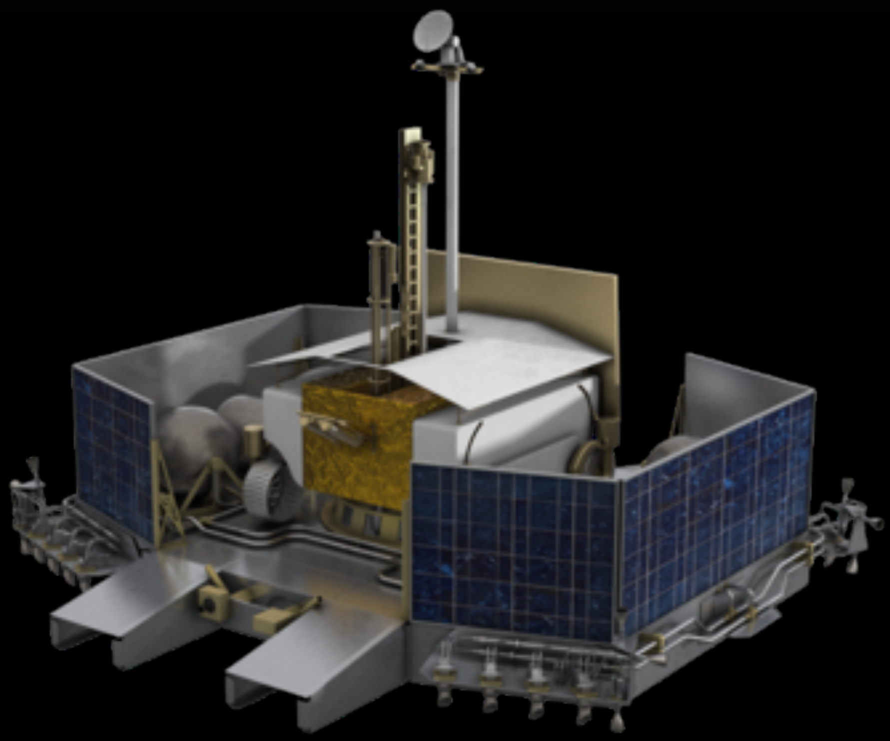
Living off the Extra-Terrestrial Land

- Rocks to Blocks
- Dust to Thrust

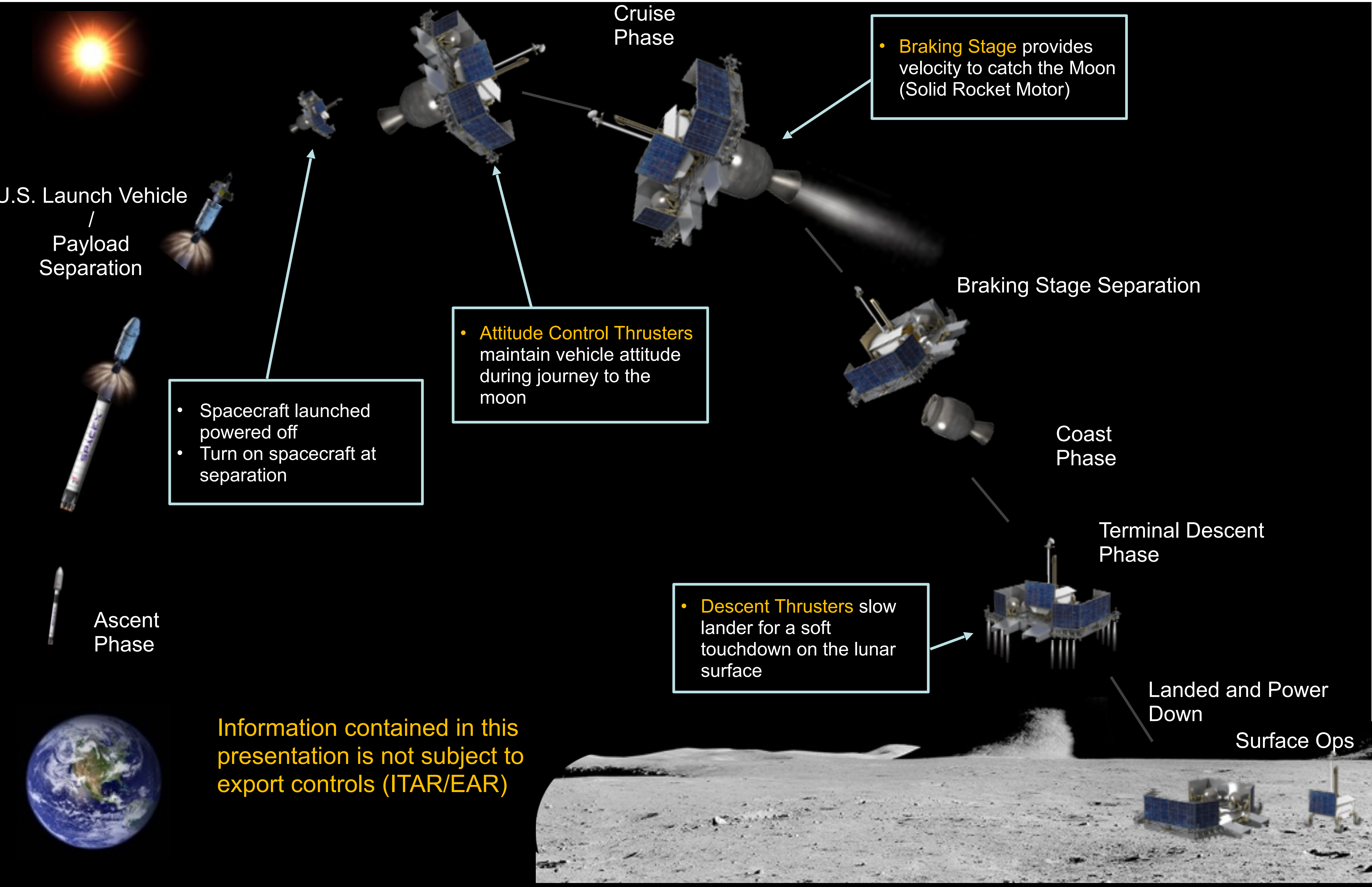
RP Mission

- Exploration Driven
- Closer to a person with a metal detector than a geologist with a hand lens
- Characterize the nature and distribution of water/volatiles in lunar polar subsurface materials
- Demonstrate ISRU processing of Lunar Regolith





Landing is a critical non-decisional ops phase



RP Mission Requirements

Landing site requirements

1.1 RESOURCE PROSPECTOR SHALL LAND AT A LUNAR POLAR REGION TO ENABLE PROSPECTING FOR VOLATILES

Full Success Criteria: Land at **a polar location** that maximizes the combined potential for obtaining a **high volatile (hydrogen)** concentration signature and **mission duration** within **traverse capabilities**

Note: balance access to shadow regions with solar power requirements

RP Measurement Requirement Summary

Paraphrased Level 2 Measurement Requirements

Minimum Success:
- Make measurements from two places separated by at least 100 meters
- Surface or subsurface measurements

Full Success (shalls):
- Measurements from two places separated by at least 1000 meters
- Surface and subsurface measurements
- Measurements in and sample acquired from shadowed area
- Demonstrate ISRU

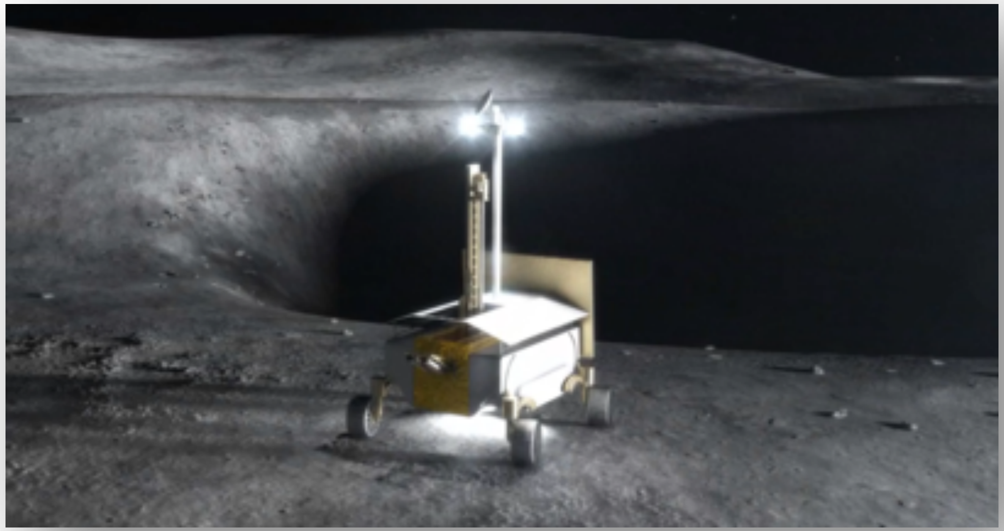
Stretch Goals (shoulds):
- Make subsurface measurements in at least eight (8) locations across 1000 m (point-to-point) distance
- Process and analyze subsurface material in at least four (4) locations across 1000 m (point-to-point) distance
- Provide geologic and thermal context

SKGs and RP – Address at Least 22 Lunar SKGs

Lunar Exploration Strategic Knowledge Gaps			Instrument or Activity	RP Relevance
I. Understand the Lunar Resource Potential				
	D-3	Geotechnical characteristics of cold traps	NIRVSS, Drill, Rover	H
	D-4	Physiography and accessibility of cold traps	Rover-PSR traverses, Drill, Cameras	VH
	D-6	Earth visibility timing and extent	Mission Planning	VH
	D-7	Concentration of water and other volatiles species within depth of 1-2 m	NSS, NIRVSS, OVEN-LAVA	VH
	D-8	Variability of water concentration on scales of 10's of meters	NSS, NIRVSS, OVEN-LAVA	VH
	D-9	Mineralogical, elemental, molecular, isotopic, make up of volatiles	NIRVSS, OVEN-LAVA	VH- Volatiles LM-Minerals
	D-10	Physical nature of volatile species (e.g. pure concentrations, intergranular, globular)	NIRVSS, OVEN-LAVA	H
	D-11	Spatial and temporal distribution of OH and H2O at high latitudes	NIRVSS, OVEN-LAVA	M-H
	D-13	Monitor and model movement towards and retenion in PSR	NIRVSS, OVEN-LAVA	M
	G	Lunar ISRU production efficiency 2	Drill, OVEN-LAVA, LAVA-WDD	M
III. Understand how to work and live on the lunar surface				
	A-1	Technology for excavation of lunar resources	Drill, Rover	M
	B-2	Lunar Topography Data	Planning Products, Cameras	M
	B-3	Autonomous surface navigation	Traverse Planning, Rover	M-L
	C-1	Lunar surface trafficability: Modeling & Earth Tests	Planning, Earth Testing	M
	C-2	Lunar surface trafficability: In-situ measurements	Rover, Drill	H
	D-1	Lunar dust remediation	Rover, NIRVSS, OVEN	M
	D-2	Regolith adhesion to human systems and associated mechanical degradation	Rover, NIRVSS, OVEN, Cameras	M
	D-3	Descent/ascent engine blast ejecta velocity, departure angle, and entrainment mechanism: Modeling	Landing Site Planning, Testing	M
	D-4	Descent/ascent engine blast ejecta velocity, departure angle, and entrainment mechanism	Lander, Rover, NIRVSS	H
	F-2	Energy Storage - Polar missions	Stretch Goal: Lander, Rover	
	F-4	Power Generation - Polar missions	Rover	M

Simplified view of RP

Get there…



Find & Excavate Volatiles…

Map surface — Use the Neutron Spec & Near-IR Spec to look for Hydrogen-rich materials

Enter permanent shadows — Go to the areas with highest concentrations of volatiles, Permanently Shadowed Regions (PSRs)

Expose regolith — Use the Drill Subsystem to expose material from 1[m] depth to examine with Near-IR Spec

Collect and Process the volatiles…

Capture regolith — Use the Drill Subsystem to capture samples from up to 1[m] depth

Heat regolith — Heat samples (150-450 degC) in the OVEN Subsystem

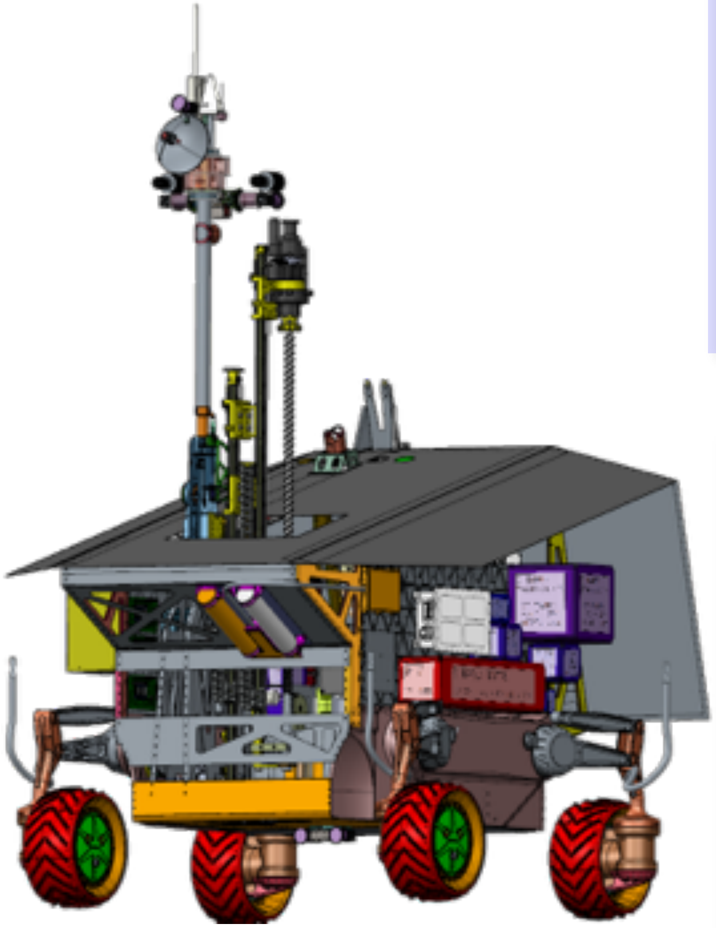
Identify Volatiles — Determine type and quantity of volatiles in the LAVA Subsystem, (H_2, He, CO, CO_2, CH_4, H_2O, N_2, NH_3, H_2S, SO_2)

Show me the water! — Image and quantify the water created using the LAVA Subsystem

Resource Prospector – The Tool Box

Mobility

Rover
- Mobility system
- Cameras
- Surface interaction



Prospecting

Neutron Spectrometer System (NSS)
- Water-equivalent hydrogen > 0.5 wt% down to 1 meter depth

NIR Volatiles Spectrometer System (NIRVSS)
- Surface H2O/OH identification
- Near-subsurface sample characterization
- Drill site imaging
- Drill site temperatures

Sampling

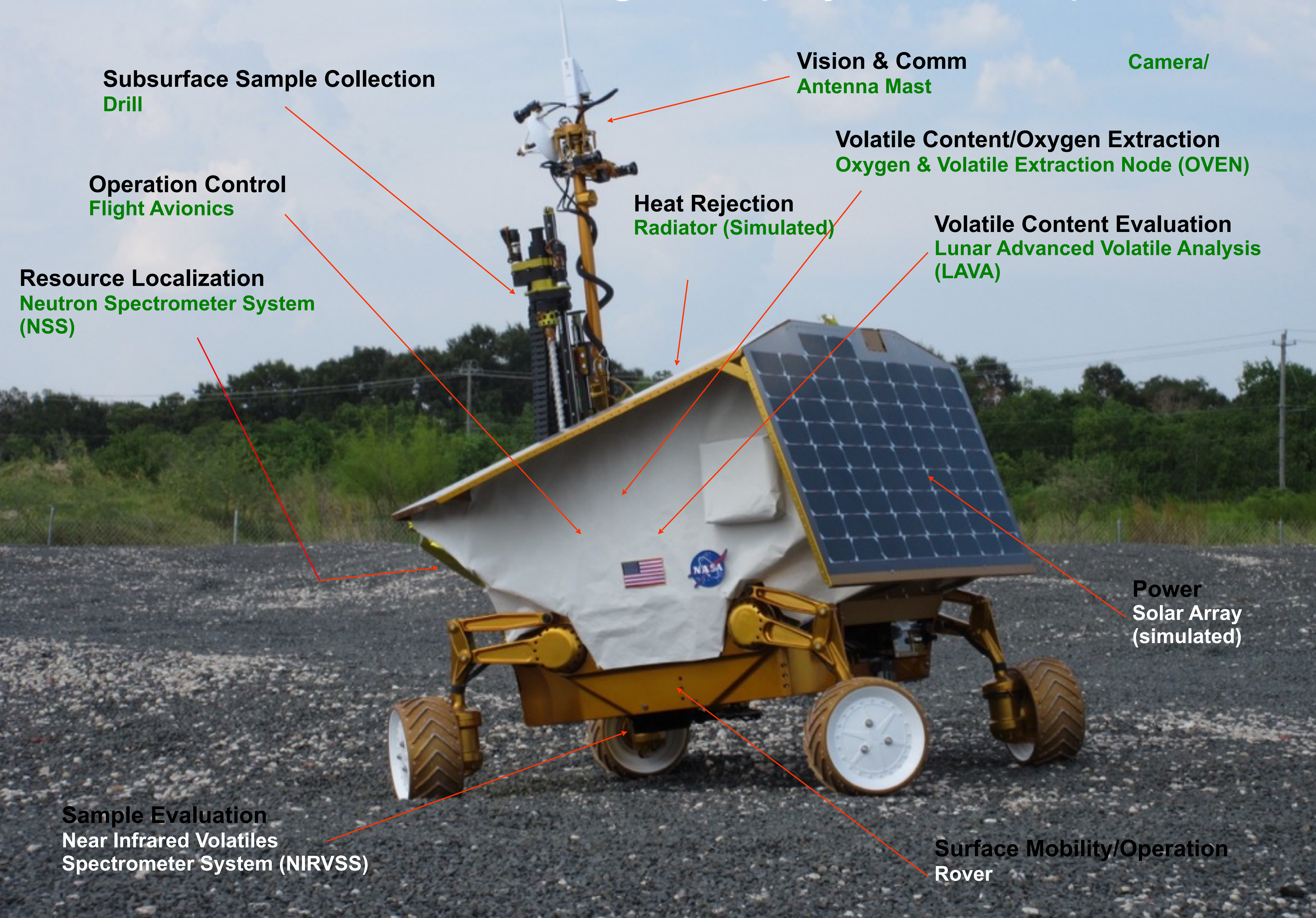
Drill
- Subsurface sample acquisition
- Auger for fast subsurface assay
- Sample transfer for detailed subsurface assay

Processing & Analysis

Oxygen & Volatile Extraction Node (OVEN)
- Volatile Content/Oxygen Extraction by warming
- Total sample mass

Lunar Advanced Volatile Analysis (LAVA)
- Analytical volatile identification and quantification in delivered sample with GC/MS
- Measure water content of regolith at 0.5% (weight) or greater
- Characterize volatiles of interest below 70 AMU

RP15: Surface Segment (Payload/Rover)

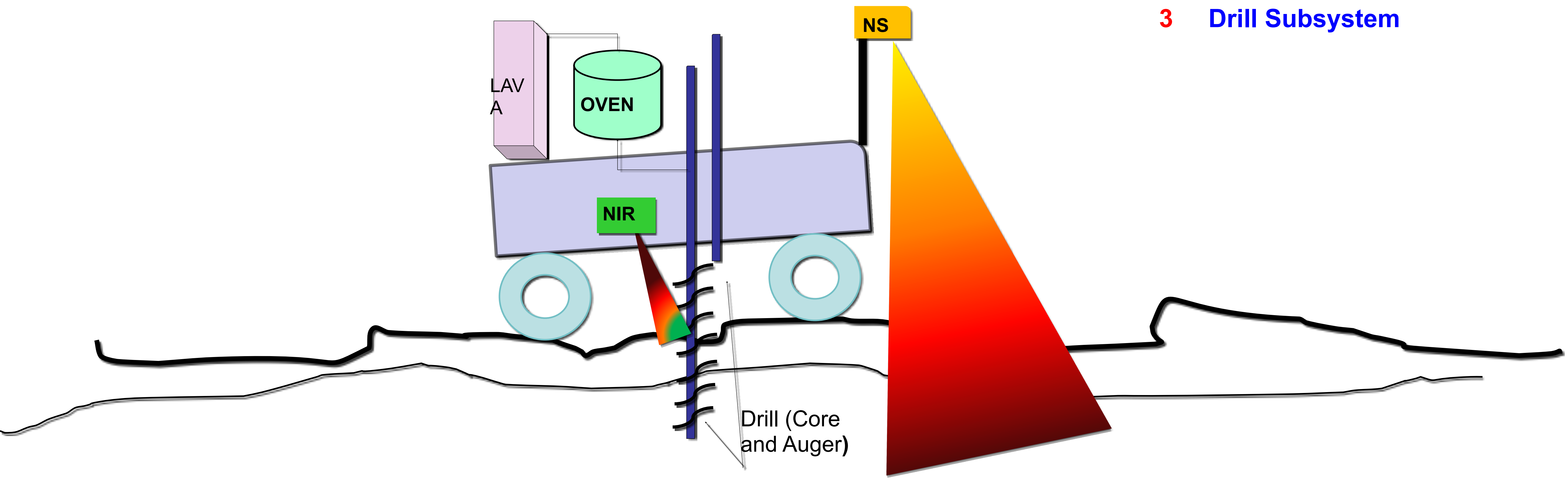


Payload Overview

5 Lunar Advanced Volatile Analysis (LAVA) Subsystem

4 Oxygen and Volatile Extraction Node (OVEN) Subsystem

3 Drill Subsystem

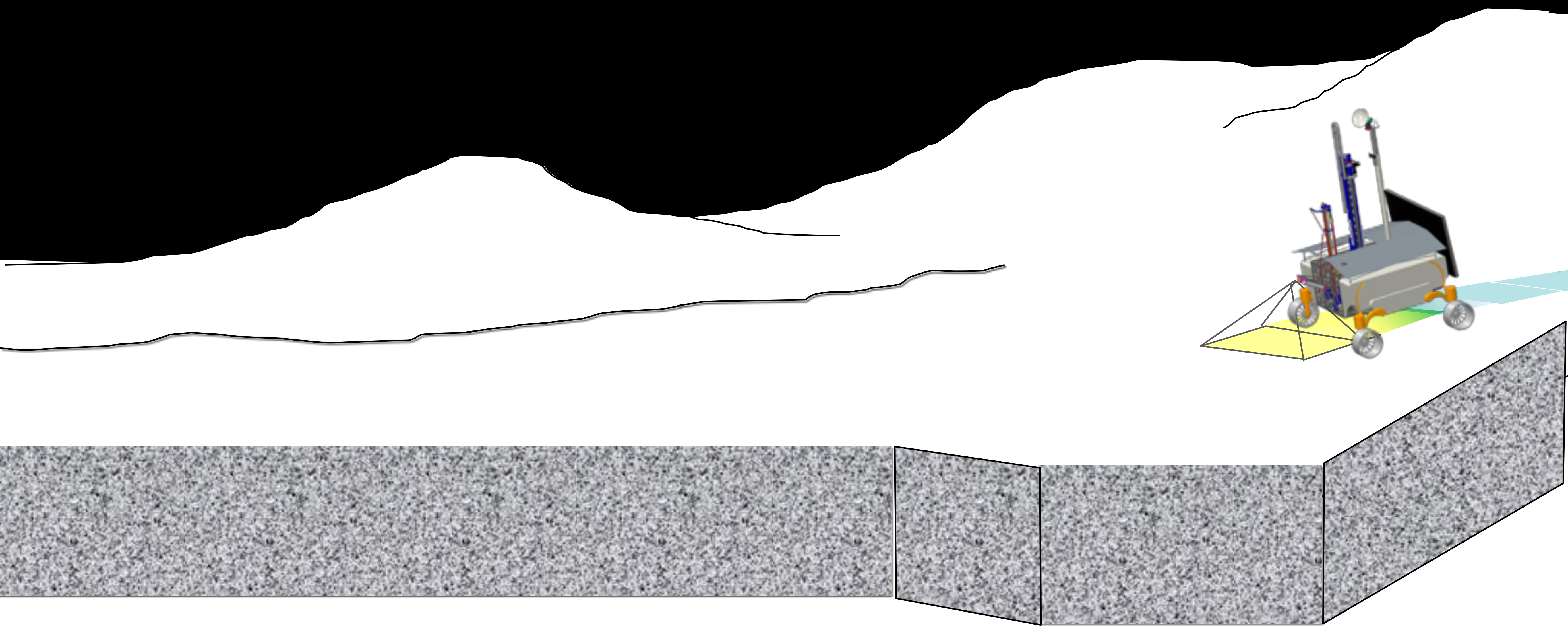


2 Near Infrared (NIR) Spectrometer Subsystem

1 Neutron Spectrometer (NS) Subsystem

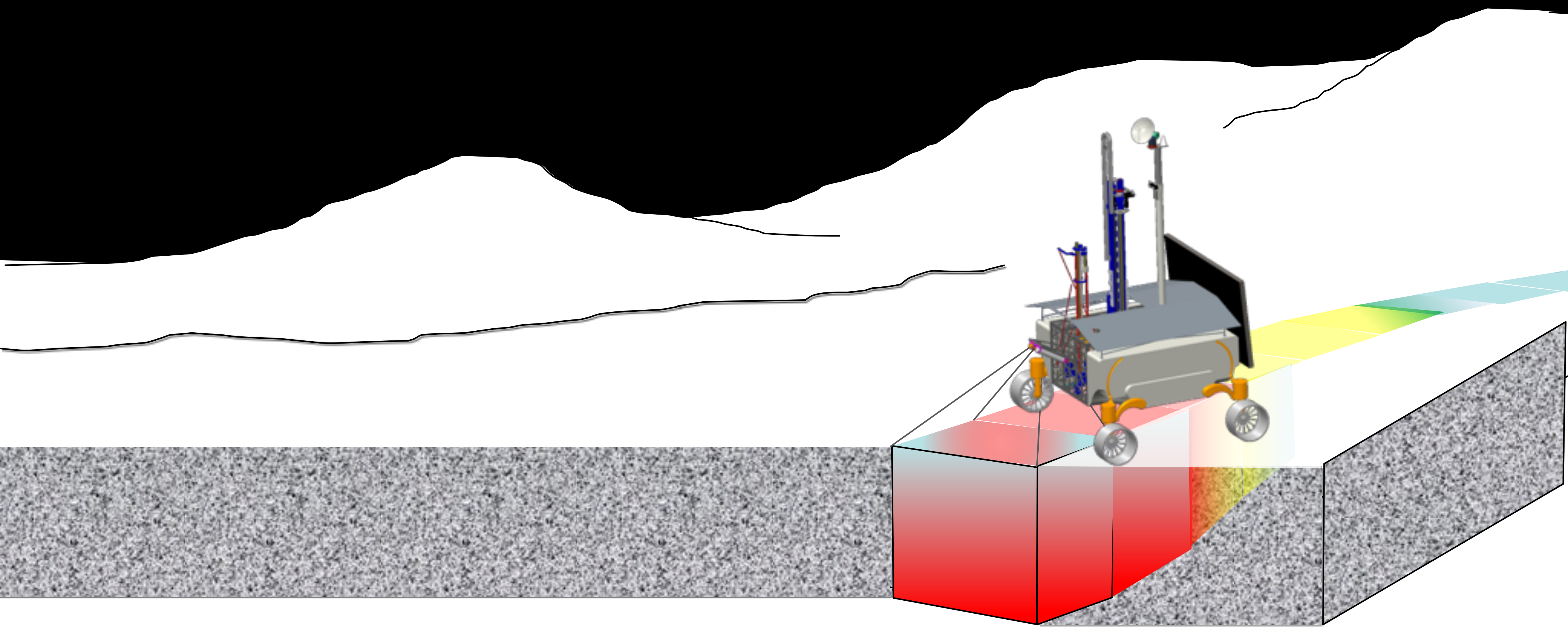
Prospecting…

1. **While roving, prospecting instruments search for enhanced surface H2O/OH, other volatiles and volumetric hydrogen**



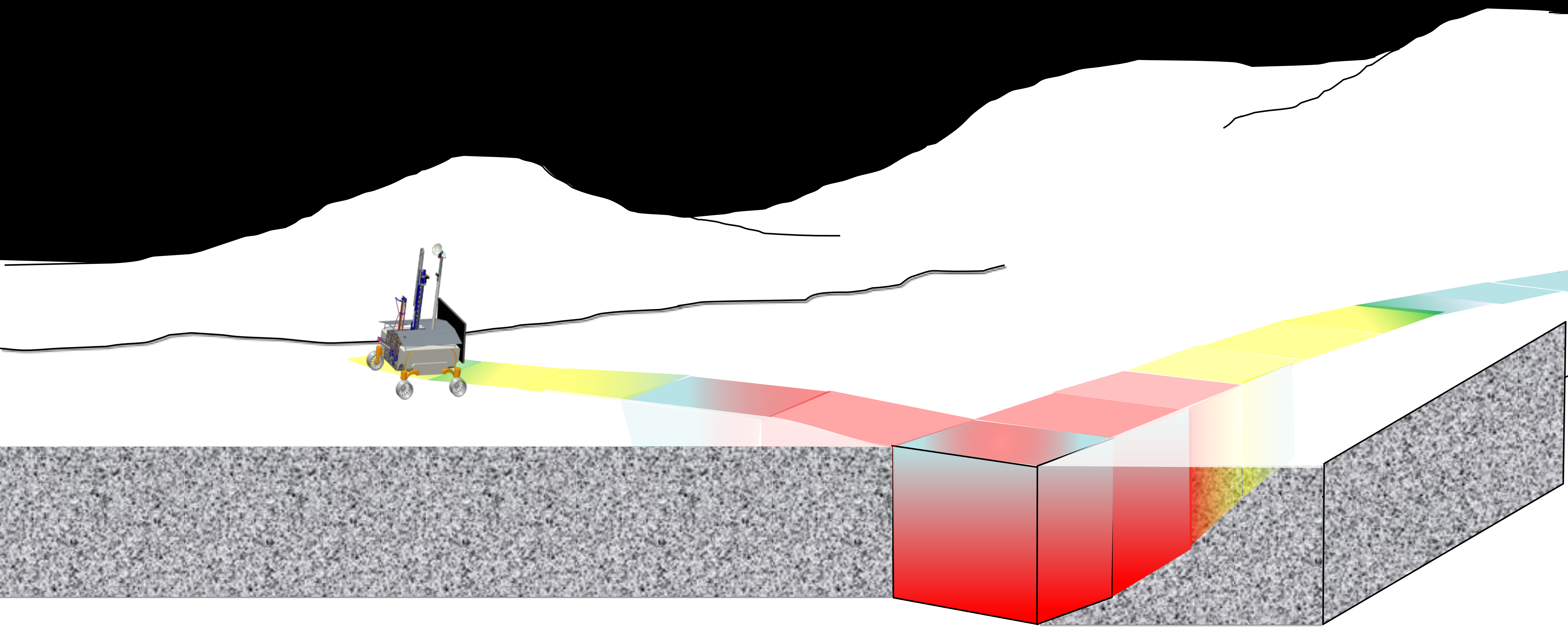
Prospecting…

1. While roving, prospecting instruments search for enhanced surface H2O/OH and volumetric hydrogen
2. When enhancements are found decision made to either auger or core (sample)



Mapping…

Mapping of volatiles and samples continue across a variety environments, testing theories of emplacement and retention, and constraining economics of extraction.



Instruments

- NSS - sniffer as we prospect - samples down to 80 cm, will tell you there is hydrogen volumetrically, will not tell you what it is or distribution with depth

- NIRVSS - Sees the surface provides form (compound) and distribution with depth (with the drill).

- NSS maps out hydrogen as we drive, NIRVSS helps understand what NSS is seeing, e.g. hydrogen in the form of water with depth

- Precise measurements of compounds with LAVA

Operations is…

- Operating/flying the vehicles
  - Lander, Rover, Payload
- Mission Operations System (MOS)
- Ground Data System (GDS)
- Mission System (MS) = MOS + GDS
- Potential for space based assets in the future, will this be cost effective?
- Design for operability

Operations is…

- Command and Control
- Planning, Trajectory, Traverse
- Vehicle health
- Data analysis (science and vehicle)
- Operational Decisions
  - Mission safety
  - Mission Success

Ops Team

- Has inputs into flight system design for operability
- Designs the processes, procedures, flight rules...
  - Example: Rover battery state of charge shall not fall below 20%
- Use the ops processes as much as possible during design, development and test of the flight system

RP Operational Design Characteristics

- Short Earth-Moon distance
  - Near real-time command and control
  - Reactive operations
  - Variable length/unpredictable round trip comm time
- Short duration surface mission
- Solar Power/Batteries
- Exploration driven goals
- 24/7 operational space assets with continuous comm
- Lighting, shadow, communications
- Class-D Mission

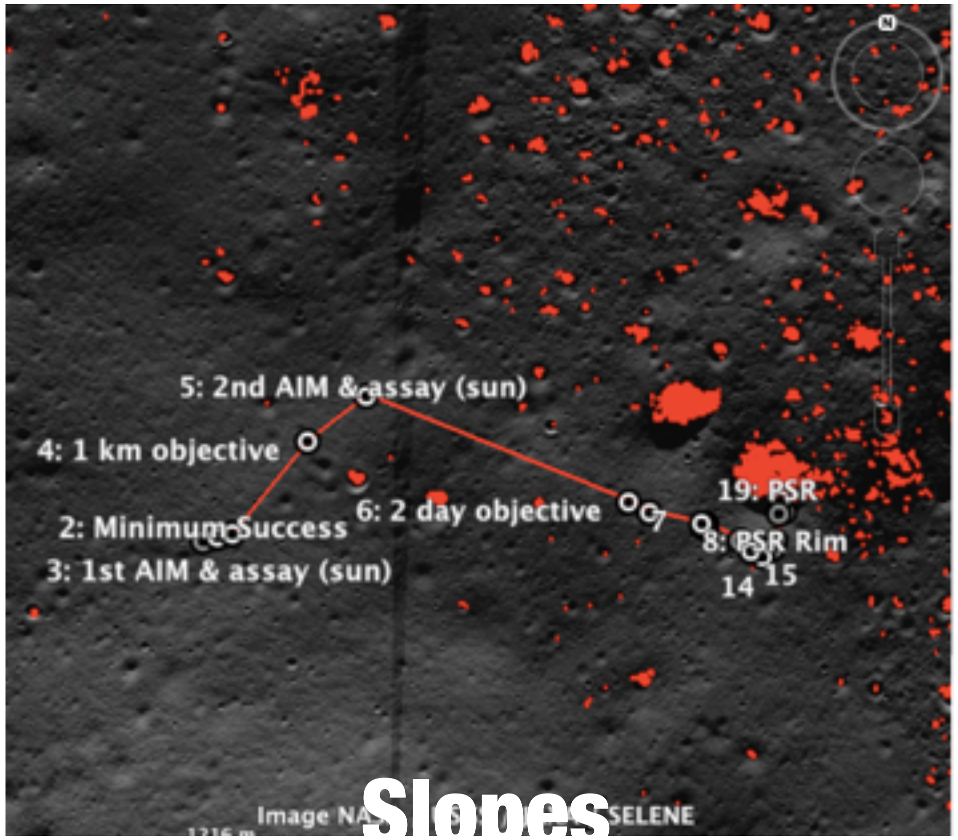
Driving Structure

- Stations
  - Sites for exploration, science team directed goals
- Rails
  - Waypoint driving, focus on reaching destination
  - Engineering driven with science interrupt capability based on sensor data with pre-determined thresholds

Traverse Plan Data/Model Inputs

The traverse plan includes the following inputs:

- **Solar illumination as a function of time**
- **Direct to Earth (DTE) communications coverage as a function of time**
- **Terrain slopes**
- **Camera imagery**
- **PSR (Permanently Shadowed Region) locations**



Slopes

Generalizable Lunar Operations

- Principles
  - Command and Control
  - Planning
  - Data
  - Polar Landscape
  - “Hermite” Example
  - Lighting and Shadow
  - Localization
  - Thermal
  - Computational Resources

Command and Control

- Short Earth-Moon distance enables distribution of tasks from Earth to space based assets that are not possible with longer distance
  - Near-real time command and control
  - Reactive Operations
- Autonomy not a requirement for high surface productivity but it is an option
- Consider ISS v. Shuttle Example
  - Shuttle mostly flown from onboard, ISS mostly flown from the ground because of high value of crew time
  - Consider using Earth based teams where possible, it may be more cost effective

Planning

- Strategic
  - RP example - each strategic plan looks at the complete set of mission objectives, what's accomplished, what remains
- Tactical
  - Current concept is based on planning from station to station within operations shift boundaries
  - 24/7 asset with continuous comm, no constraints such as consumables or EVA time, but we do have to recharge
  - Apollo 17 orange soil example
- Reactive
  - Based on sensor inputs in real time
  - Ground decision time is a significant driver for mission productivity
- Lunar port fuel production goals should allow for quantifiable planning objectives based on goals

Data

- Use of Earth based resources for ongoing surface operations challenge current communications capability in both availability and data rates
- Current Communications system capabilities impose overhead that adds latency and variability
  - 6 seconds - 25 seconds (or longer) latency
- Current systems are shared resources across deep space missions
- Imagine
  - Dedicated laser communications

Polar Landscape

- Poles are highlands material
- Mega - regolith, 50m - 80m deep
- Few obvious rocks at the surface that we can see, different landscape than the equator
- Rock densities in the highlands on average much less than in the Mare
- Issue is negative relief, i.e. craters in the fluff

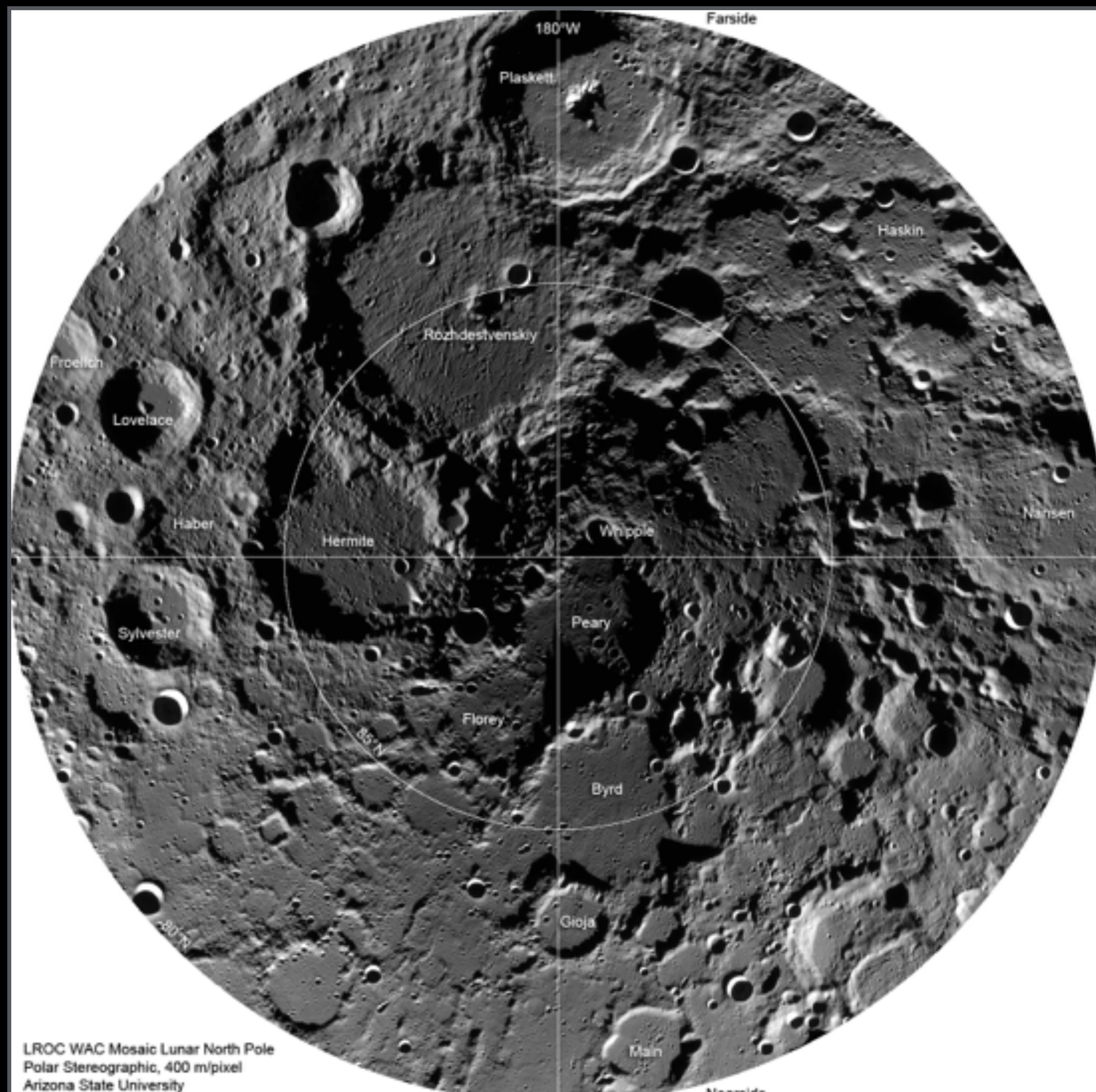
Terrain

- Impact gardening from micro-meteorites
- Thermal cycles settle down the dust fluff from impact gardening
- So PSR's may have loose fluffy soil... analogy for rover driving, design a car to drive on the road but you're driving on a beach
- Thermal cycling at the poles is less than at the equatorial sites
- Expect less consolidated material
- 50% to 2x more fluff than at the equator in the top 10 cm
- Don't know how much porosity increases or extends
- Bigger wheels to accommodate for this
- The way you get stuck is you slip and try to get out, wheel ribs to keep you from slipping, area to keep you from sinking

PSR

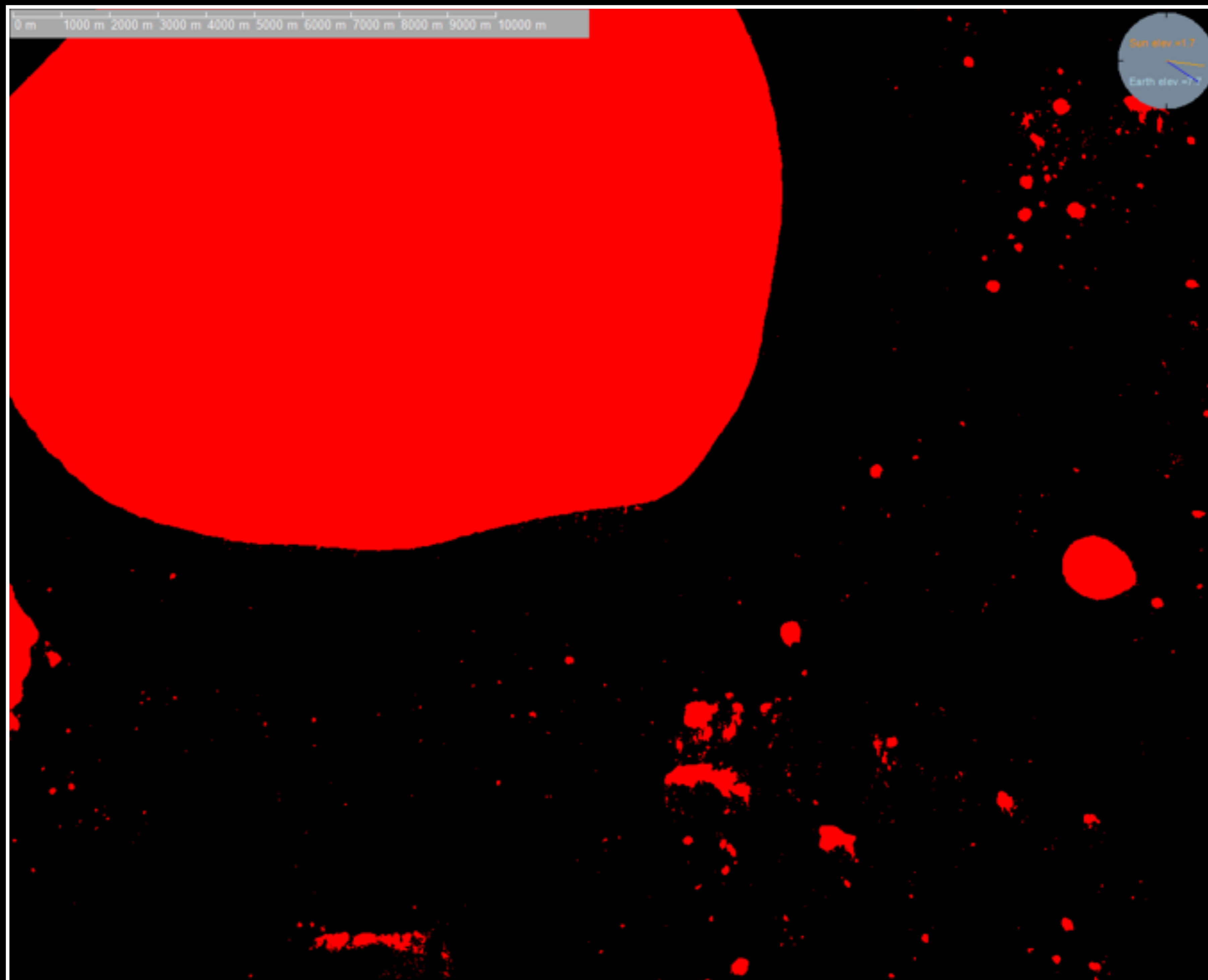
- Permanently Shadowed Regions (PSR)
  - Best places to search for volatiles
  - In shadow for geologically significant period of time (hundreds of millions of years)
- PSR - no thermal cycling, so meteoritic dust or volatiles that get trapped are not getting consolidated or compacted
- So PSR's may have loose fluffy soil... analogy for rover driving, design a car to drive on the road but you're driving on a beach
- Cold, in 40 degree K range (-387.7 deg F, -233.1 deg C)
- For RP, duration of stay limited by power (solar/battery). Battery drain may start before entering PSR because the approach path may be in shadow

Hermite

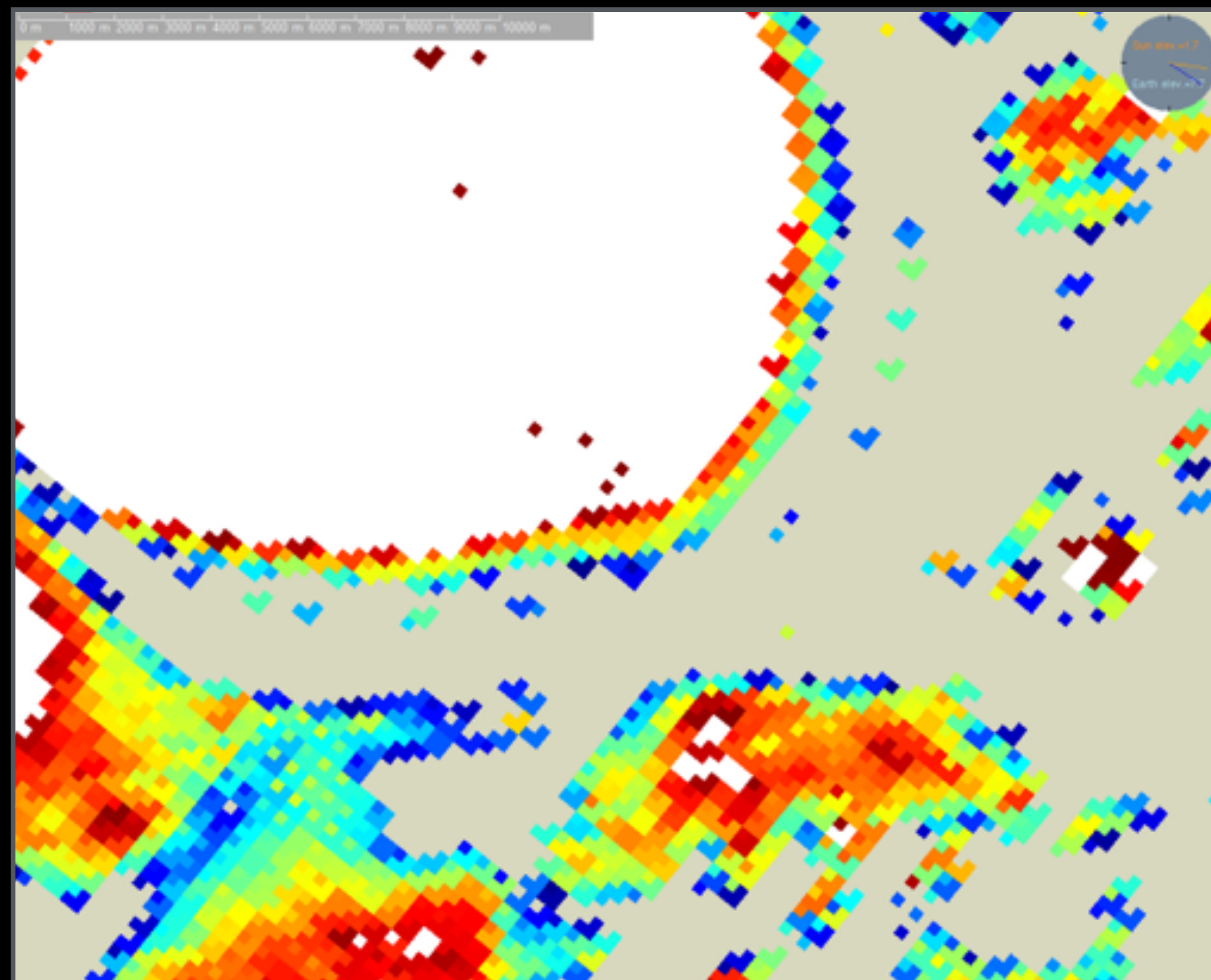


180°W
Farside
Plaskett
Haskin
Rozhdestvenskiy
Froelich
Lovelace
Haber
Hermite
Whipple
Nansen
Sylvester
Peary
Florey
85°N
Byrd
80°N
Gioja
Main
Nearside
LROC WAC Mosaic Lunar North Pole
Polar Stereographic, 400 m/pixel
Arizona State University

Permanent Shadow



Ice Stability Depth

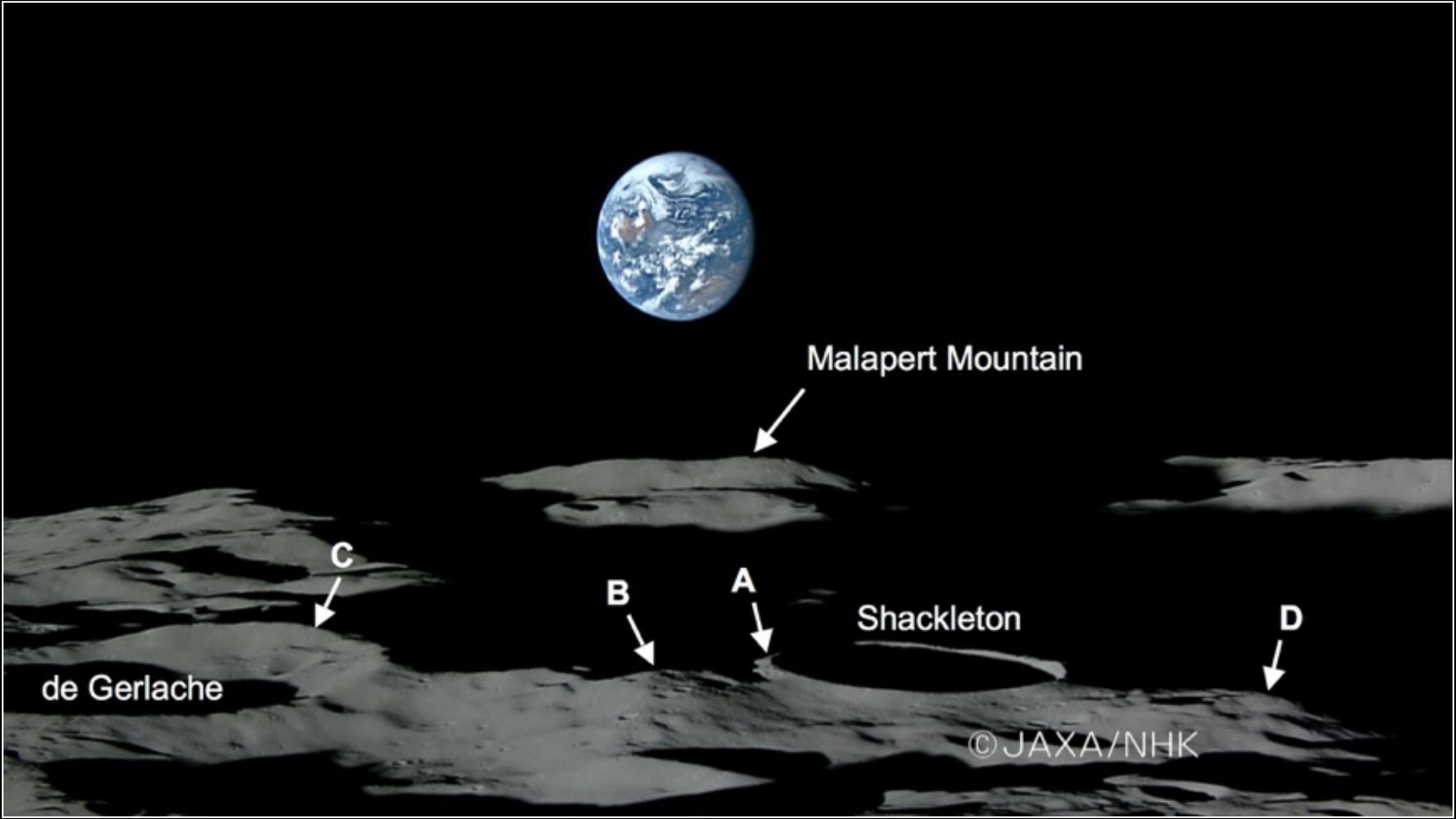


Ice stable in vacuum over geologically significant periods of time, white means stable on the surface (PSR), 1 pixel = 240m square, grey means depth > 1m, red - blue just under surface to 1m (for 1m drill)

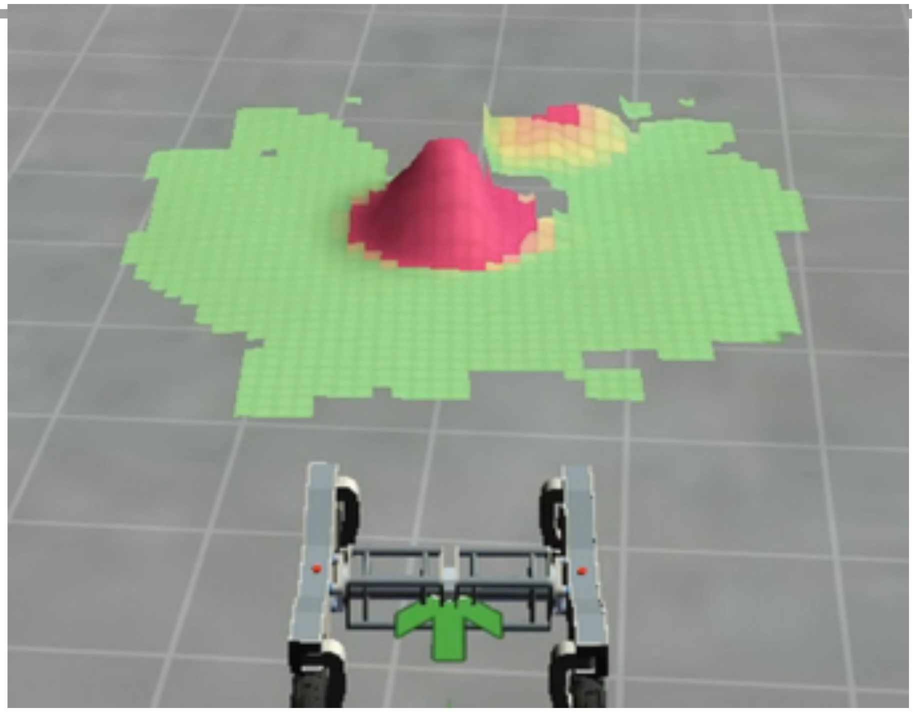
Lighting and Shadow

- Low Sun Angles
  - Optics for driving
  - Solar power
- Shadows are
  - Almost pure black, no atmospheric reflection
  - In black regions, minimal illumination
    - Interior reflection, sun light bouncing off a rock or crater wall
    - Earth Shine
    - Starlight
  - Rover needs it's own lighting, LIDAR too expensive for RP but recommended

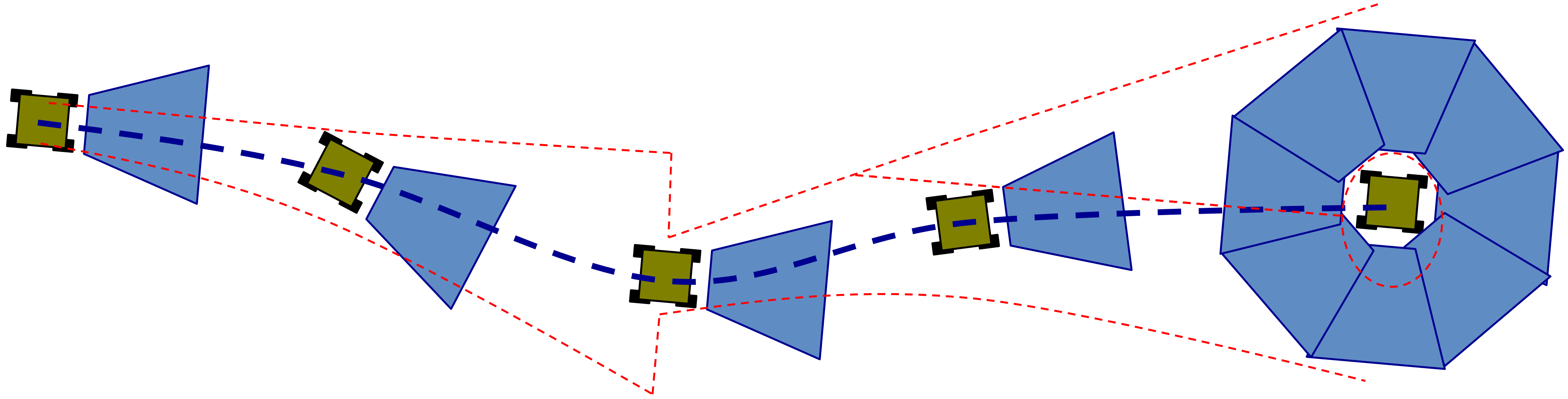
Polar Illumination



Navigation / Ops Approach



- Hazard detection and path selection
  - Highly interactive, not long command sequences
    - Stereo cameras take pictures, send to ground
    - Ground SW builds 3D models, identifies hazards
    - Operator plans near-field path, sends commands
  - Looking at onboard halt-on-hazard “virtual bumper”
- Localization
  - Onboard SW tracks position using IMU, star tracker, wheel odometry
  - Ground SW improves position using visual odometry, smoothing
  - Periodic position fix by registering rover panoramas to orbital DEM

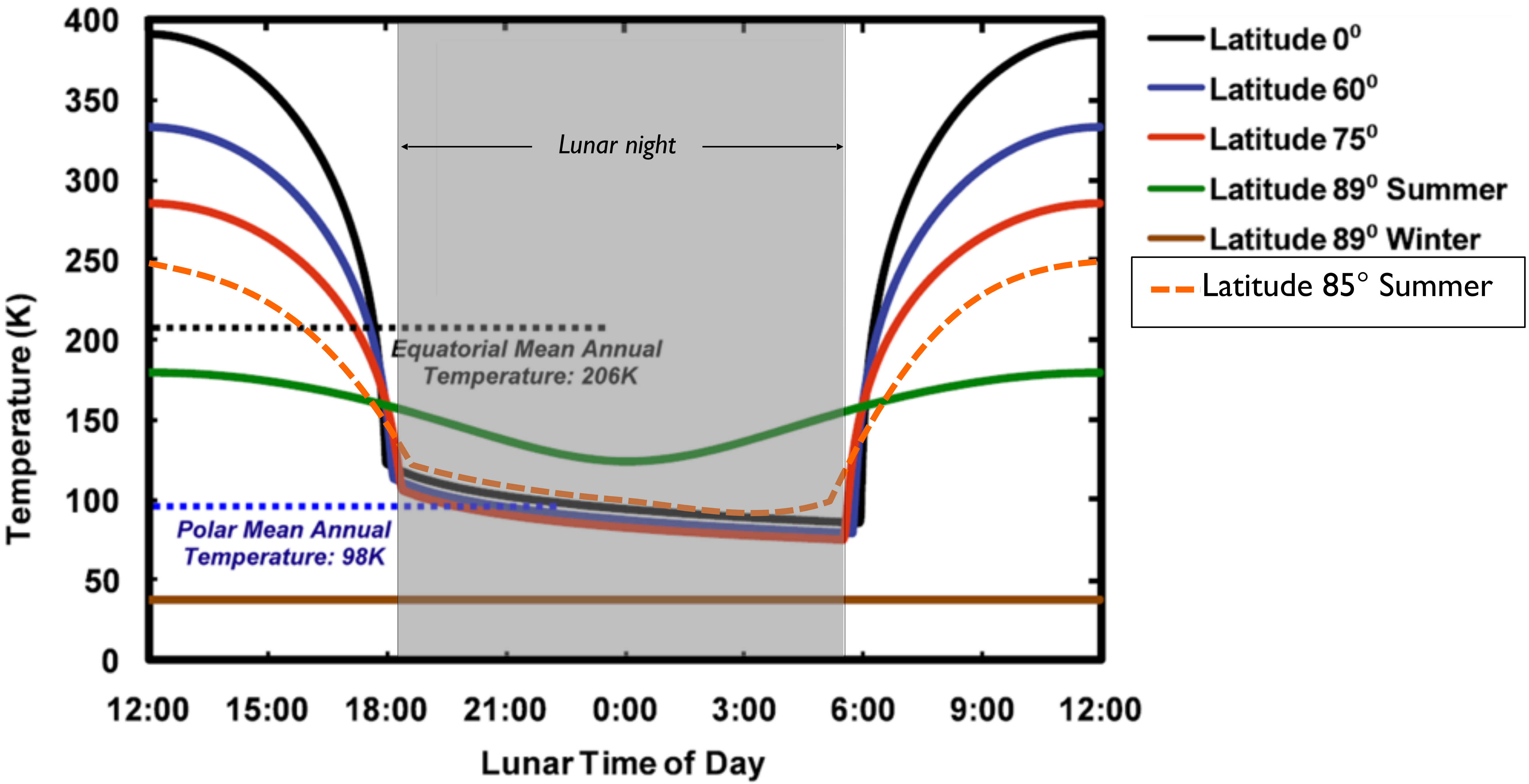


Thermal

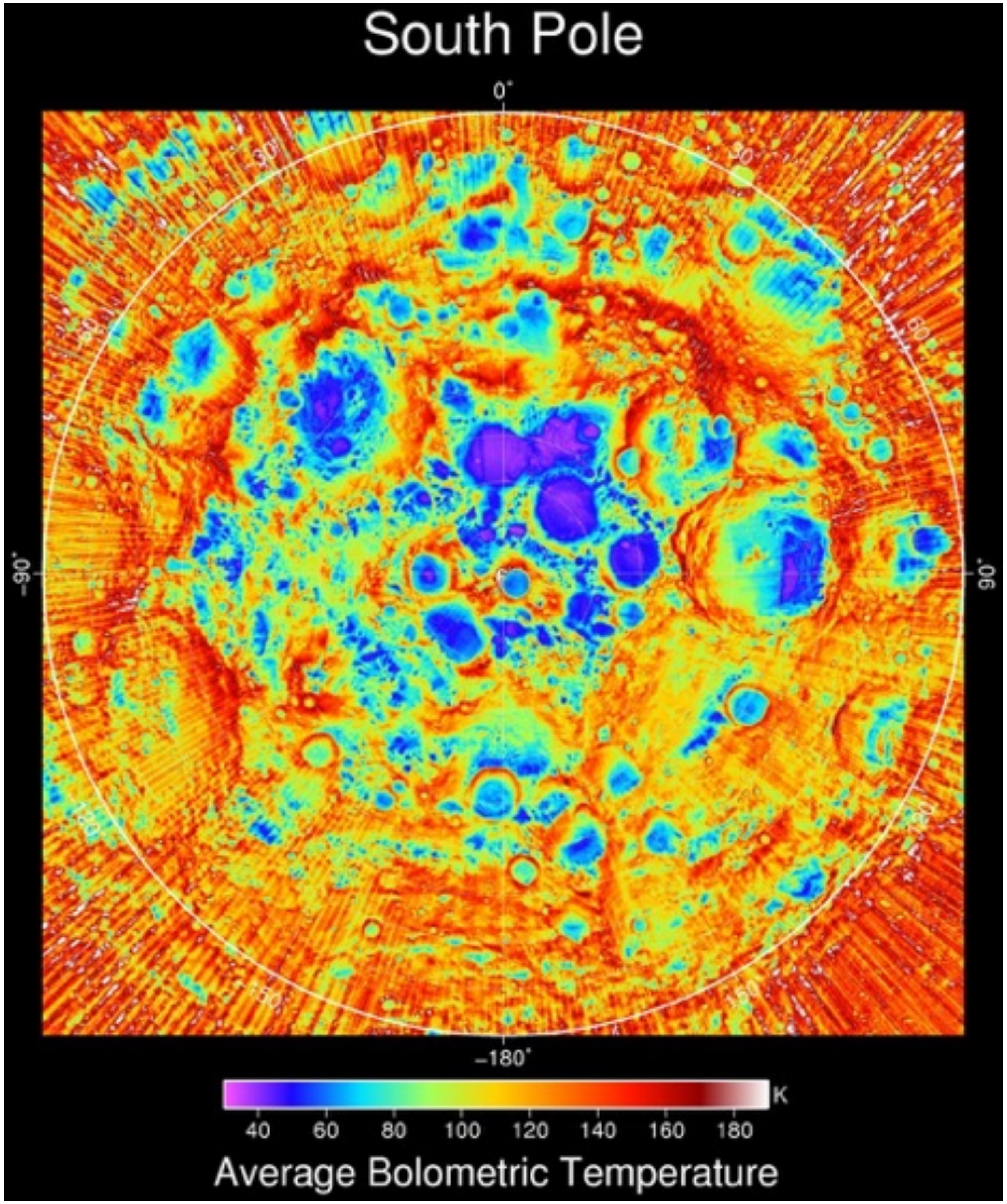
- ~40k inside PSR (-387.7 deg F, -233.1 deg C)
- System design problem for operability and survivability
- Thermal management is a significant operational issue and is tracked continuously in real time
- Lunar day/night cycle 28 days
- Lunar arctic circle
- Tilt is ~1.5 degrees

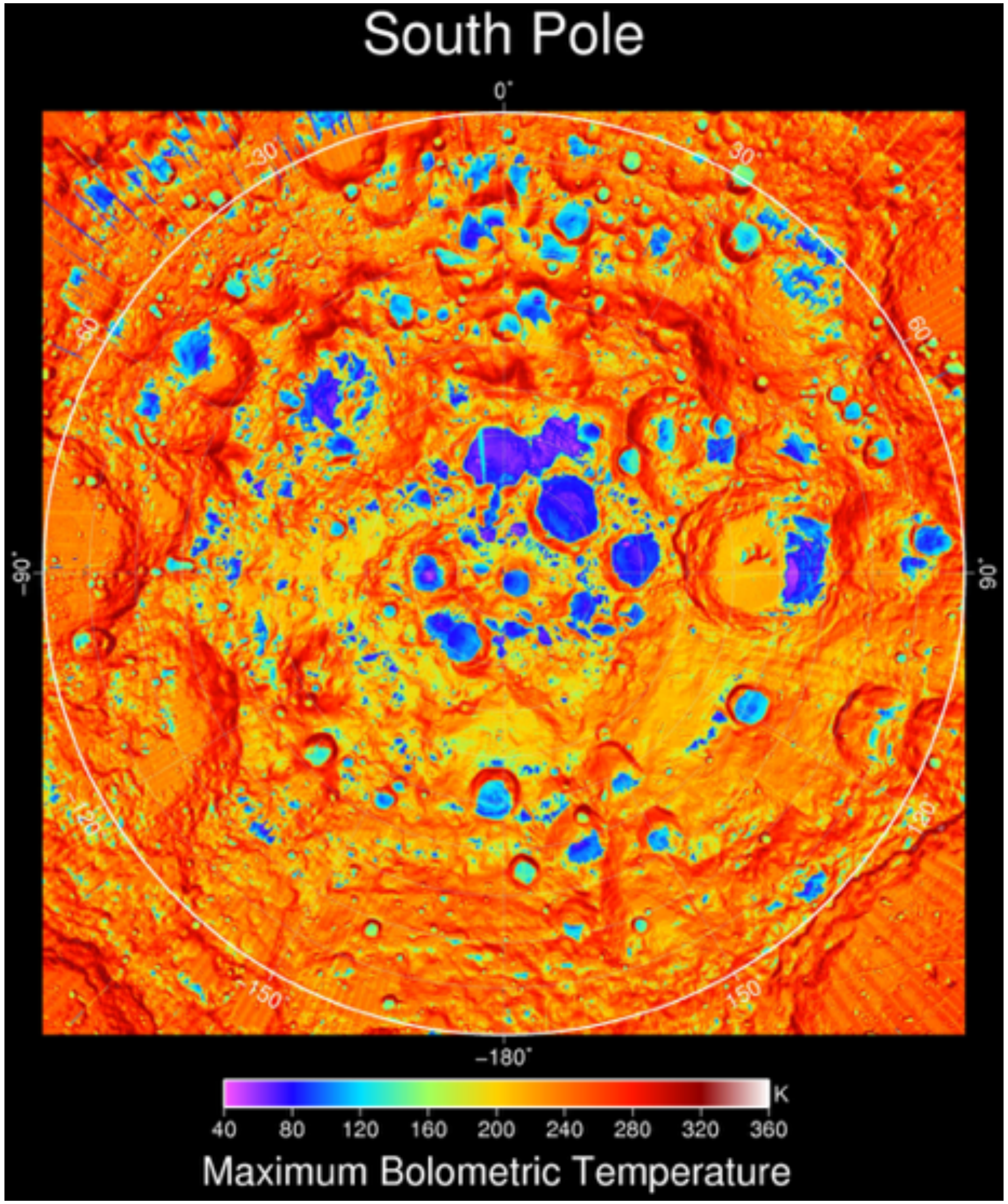
Lunar Environment: Thermal

Figure from Paige et al., 2010



Lunar Environment: Thermal

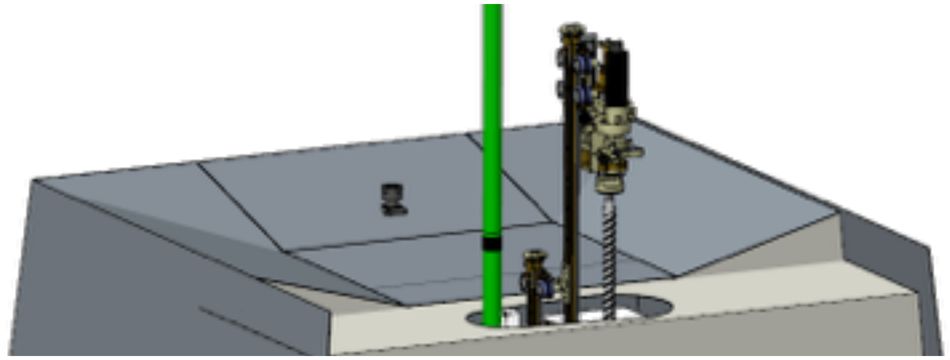




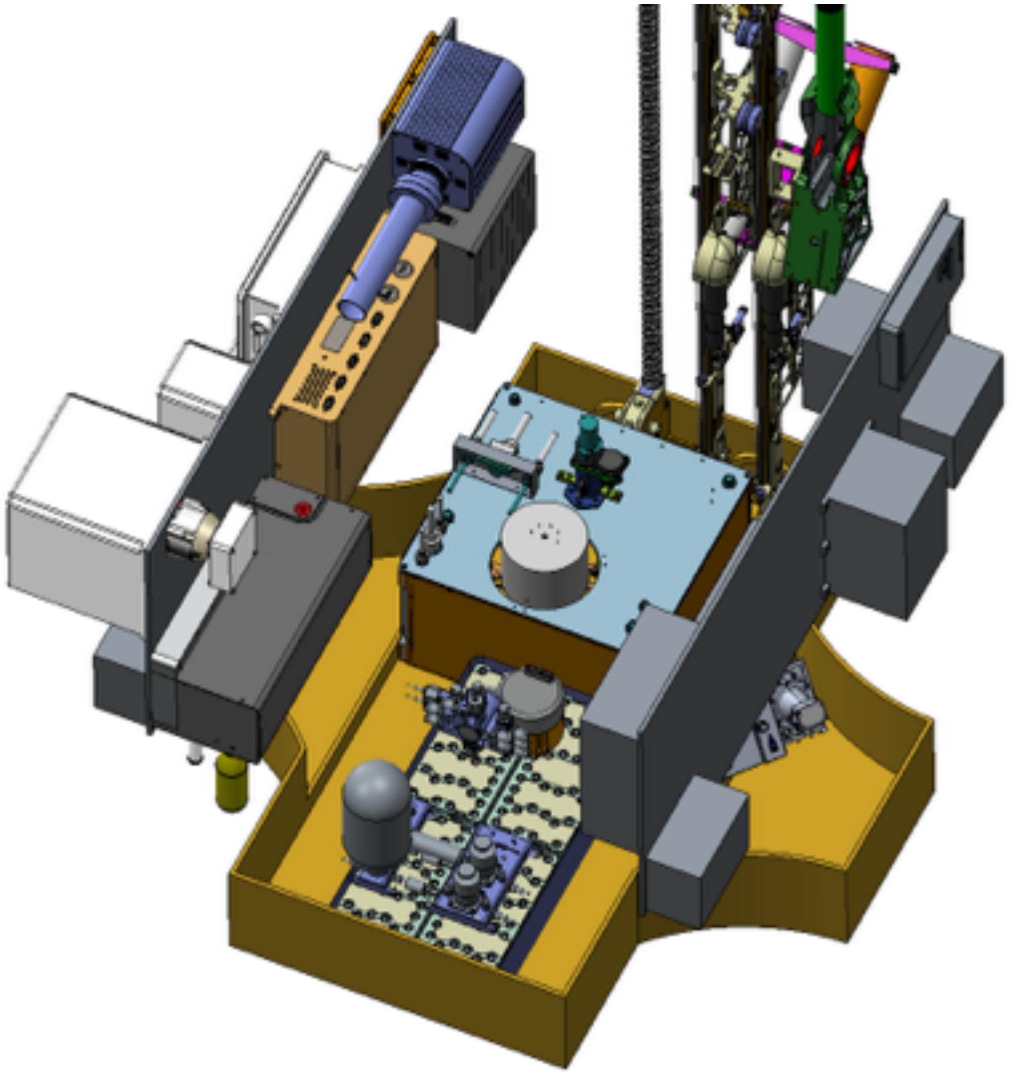
RP1A Thermal Overview

Thermal Control Systems

- Separated controlled zones
  - Main body
  - Battery
  - Wheel Modules
  - Mast and Gimbals
  - *Solar Array Panels



- 2x Dual sided heat spreaders with heat pipes
- Single radiator with head pipes
- ~4x Variable conductance heat pipes
  - Connect heat spreaders to radiator
- Selectively placed heaters
- Selectively place temp sensors
- Thermal straps to wheel modules
- 3 solar panels spreading out heat with heat pipes



Computation

- Innate tendency is to want to do things on board
  - Doing things onboard, even when close to Earth, may not be the most cost effective, e.g. significant ISS ops done from Earth to maximize crew productivity for things that can only be done in space
  - Mars rover - stereo processing onboard
  - Resource Prospector Lunar Rover - stereo processing done on the ground
- Given sufficient comm bandwidth it would be possible to have significant computational power on Earth
  - AWS for Space...

Ops Thoughts

- Autonomous
- Lights Out
- Intelligent Notifications

Acknowledgements

- Thanks for the content
  - Dan Andrews
  - Tony Colaprete
  - Matt Deans
  - Mark Shirley