Lunar Polar Volatile Strategy –
Resource Prospector Mission (RPM) and Beyond

Space Resources Roundtable/ Planetary and Terrestrial Mining Sciences Symposium

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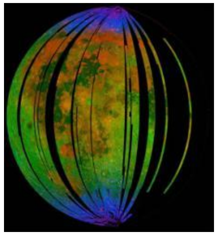
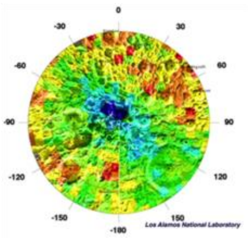
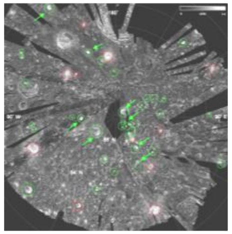
Global Assessment of Lunar Volatiles

Apollo Samples	Moon Mineralogical Mapper (M^3)	Lunar Prospector Lunar Recon Orbiter (LRO)	Lunar Crater Observation & Sensing Sat. (LCROSS)	Clementine Chandrayaan LRO Mini SAR/RF
				

	Solar Wind	Core Derived Water	Water/Hydroxyl	Polar Volatiles	Polar Ice
Instrument	Apollo samples Neutron Spectrometer	Apollo samples	M3/LRO	LCROSS	Mini SAR/RF
Concentration	Hydrogen (50 to 150 ppm) Carbon (100 to 150 ppm) Helium (3 to 50 ppm)	0.1 to 0.3 wt % water in Apatite 0 to 50 ppm water in volcanic glass	0.1 to 1% water; 1-2% frost on surface in shadowed craters	**3 to 10% Water** equivalent Solar wind & cometary volatiles **(CO, H2, NH3, organics)**	Ice layers
Location	Regolith everywhere	Regolith; Apatite	Upper latitudes	Poles	Poles; Permanent shadowed craters
Environment	Sunlit	Sunlit	Low sun angle Permanent shadow <100 K	Low or no sunlight; Temperatures sustained at <100 K	<100 K, no sunlight
Depth	Top several meters; Gardened	Top 10's of meters	Top mm's of regolith	Below 10 to 20 cm of desiccated layer	Top 2 meters

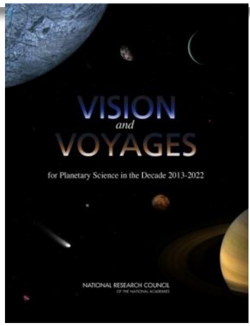
We know the water (and other H-bearing compounds) are there…

Observed Volatiles at the LCROSS Site

					Instrument			
	Column Density (# m^{-2})	Relative to H2O(g) (NIR spec only)	Concentration (%)	Long-term Vacuum Stability Temp (K)	UV/Vis	NIR	LAMP	M3
CO	1.7e13±1.5e11		5.7	15			x	
H_2O(g)	5.1(1.4)E19	1	5.50	106		x		
H_2	5.8e13±1.0e11		1.39	10			x	
H_2S	8.5(0.9)E18	0.1675	0.92	47	x	x		
Ca	3.3e12±1.3e10		0.79				x	
Hg	5.0e11±2.9e8		0.48	135			x	
NH_3	3.1(1.5)E18	0.0603	0.33	63		x		
Mg	1.3e12±5.3e9		0.19				x	
SO_2	1.6(0.4)E18	0.0319	0.18	58		x		
C_2H_4	1.6(1.7)E18	0.0312	0.17	~50		x		
CO_2	1.1(1.0)E18	0.0217	0.12	50	x	x		
CH_3OH	7.8(42)E17	0.0155	0.09	86		x		
CH_4	3.3(3.0)E17	0.0065	0.04	19		x		
OH	1.7(0.4)E16	0.0003	0.002	>300 K if adsorbed	x	x		x
H_2O (adsorb)			0.001-0.002					x
Na		1-2 kg		197	x			
CS					x			
CN					x			
NHCN					x			
NH					x			
NH_2					x			

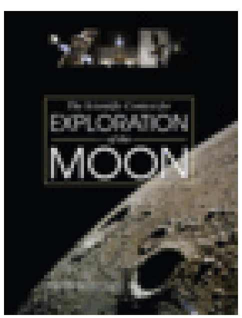
Volatiles comprise possibly 15% (or more) of LCROSS impact site regolith

Planetary Science Goals for Understanding Polar Volatiles



Building New Worlds	Planetary Habitats	Working of Solar Systems
What governed the accretion, supply of water, chemistry and internal differentiation of the inner planets?	What are the primordial sources of organic matter and where does organic synthesis continue today?	How have the myriad chemical and physical processes that shaped the solar system operated, interacted, and evolved over time?

Planetary Science Research Objectives (SMD Science Plan 2010)		
1. Inventory solar system objects and identify the processes active in and among them.	2. Understand how the Sun's family of planets, satellites, and minor bodies originated and evolved.	5. Identify and characterize small bodies and the properties of planetary environments that pose a threat to terrestrial life or exploration or provide potentially exploitable resources.



Science Concept 4 : The lunar poles are special environments that may bear witness to the volatile flux over the latter part of solar system history.

Science Goals:

4a. Determine the compositional state (elemental, isotopic, mineralogic) and compositional distribution (lateral and depth) of the volatile component in lunar polar regions.
4b. Determine the source(s) for lunar polar volatiles
4c. Understand the transport, retention, alteration, and loss processes that operate on volatile materials at permanently shaded lunar regions.
4d. Understand the physical properties of the extremely cold (and possibly volatile rich) polar regolith.
4e. Determine what the cold polar regolith reveals about the ancient solar environment.

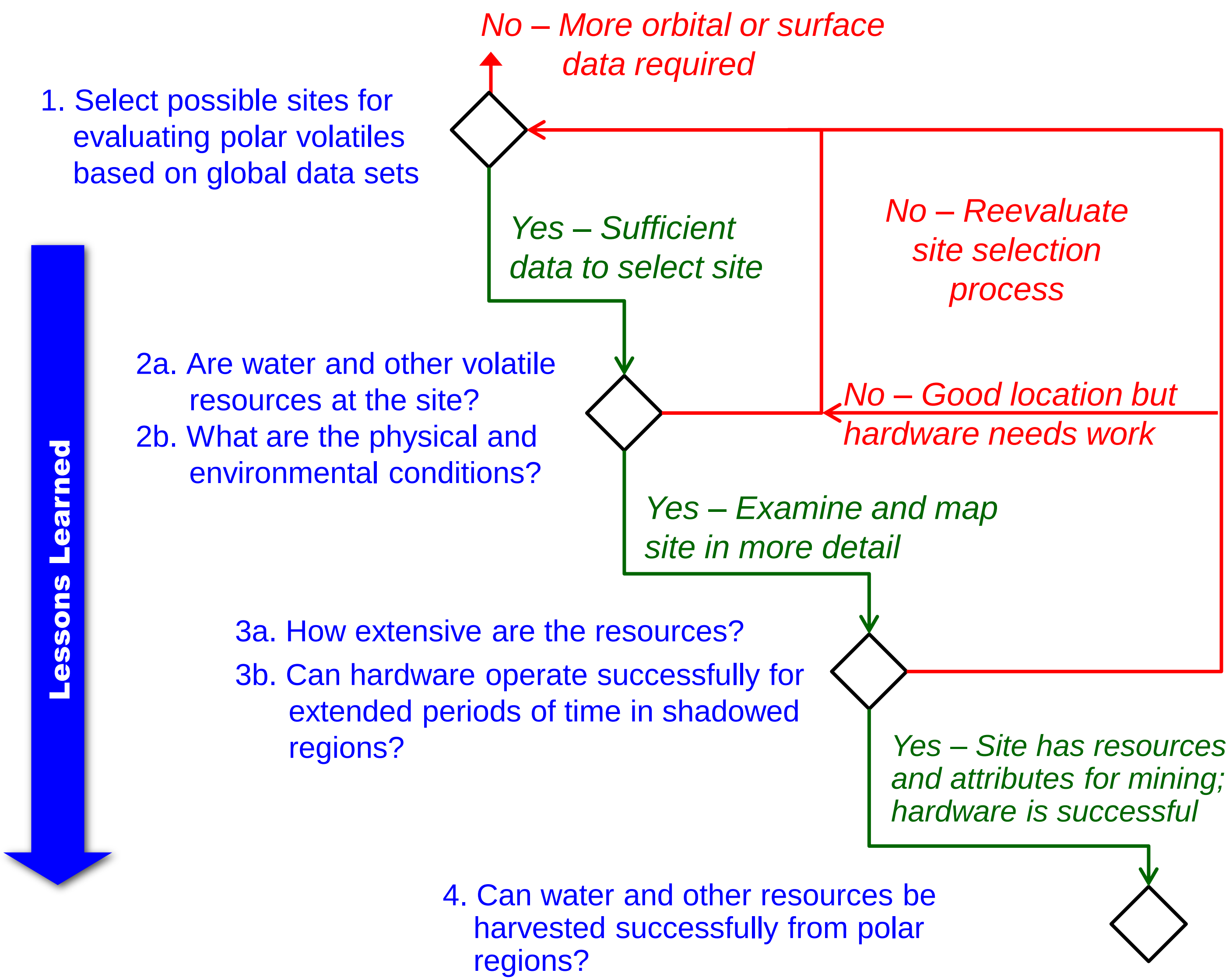
Mission Goals for Lunar Volatile Resource Usage

From *LEAG Robotic Campaign Analysis (2011):*

Phase I: Lunar Resource Prospecting

- Defining the composition, form, and extent of the resource;
- Characterizing the environment in which the resources are found;
- Defining the accessibility/extractability of the resources;
- Quantifying the geotechnical properties of the lunar regolith in the areas where resources are found;
- Being able to traverse several kilometers and sample and determine lateral and vertical distribution on meter scales;
- Identifying resource-rich sites for targeting future missions

Approach to Understanding and Utilizing Polar Volatile Resources and Retiring Risk is Required



Driving Questions

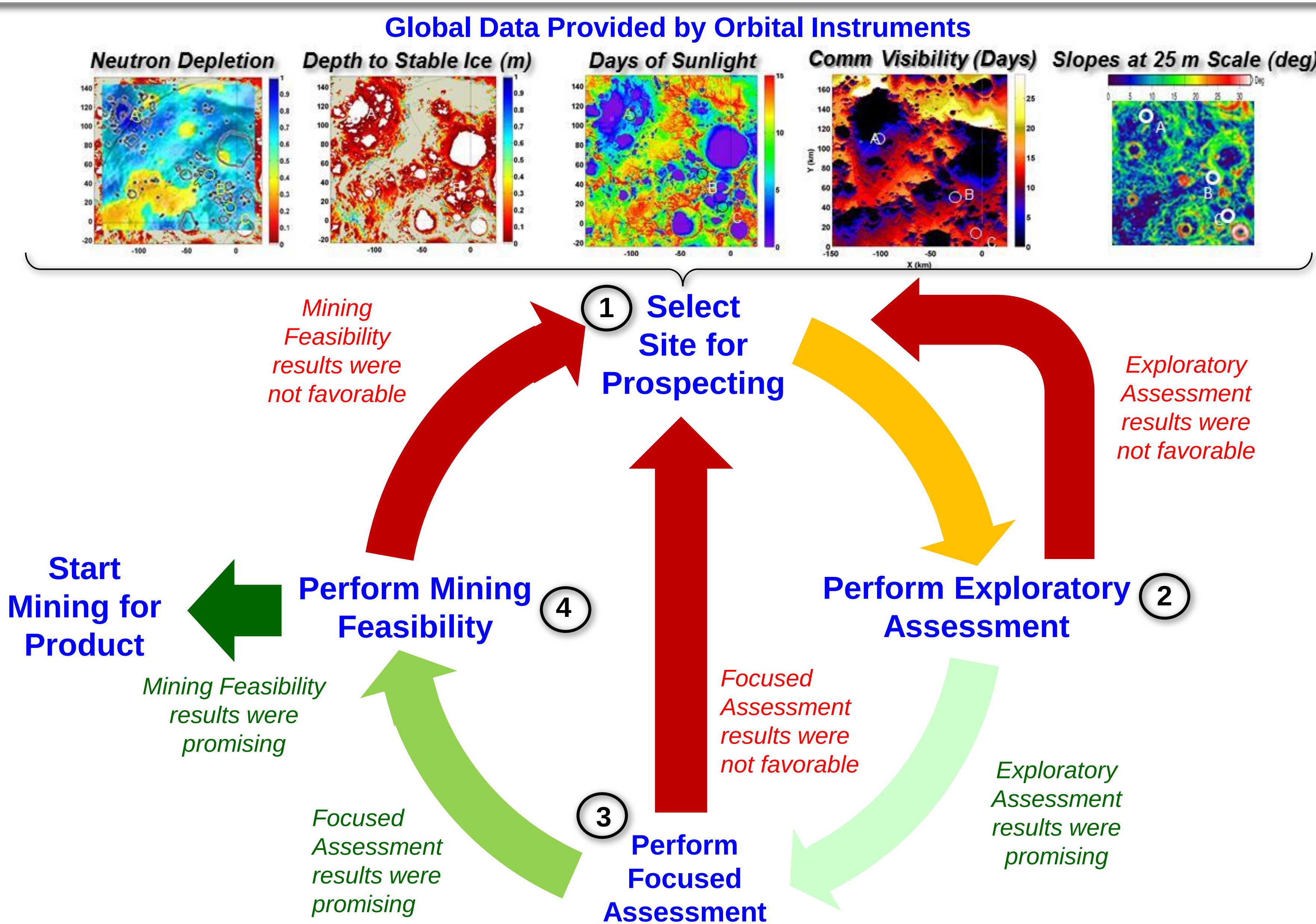
Where are polar volatiles located?

What is the form, concentration and distribution of polar resources?

Are long term operations at the lunar poles feasible'?

Is extraction of polar resources 'economical'?

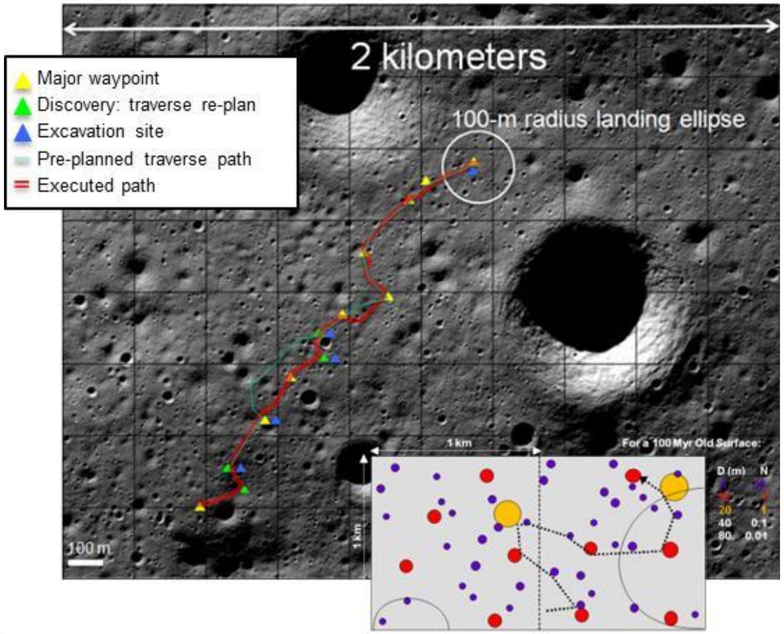
Understanding Polar Volatiles - Prospecting Cycle



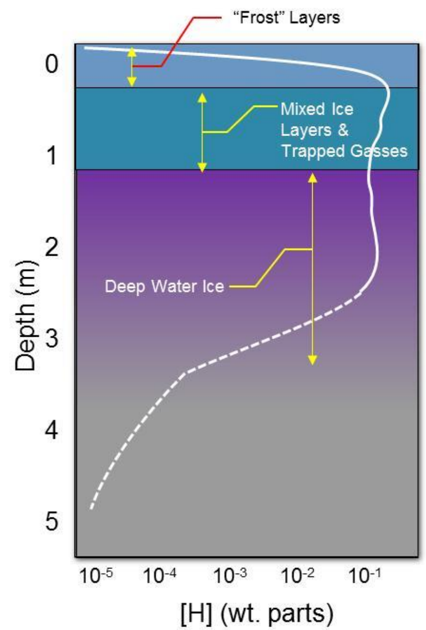
Determining 'Operationally Useful' Resource Deposits

Need to assess the extent of the resource 'ore body'

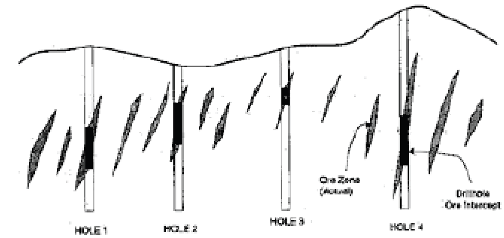
Need to Evaluate Local Region (1 to 3 km)



Need to Determine Vertical Profile



Need to Determine Distribution



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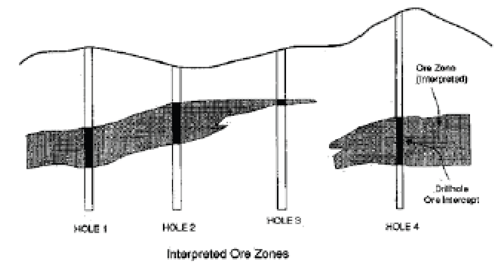


An 'Operationally Useful' Resource Depends on What is needed, How much is needed, and How often it is needed

Potential Lunar Resource Needs*

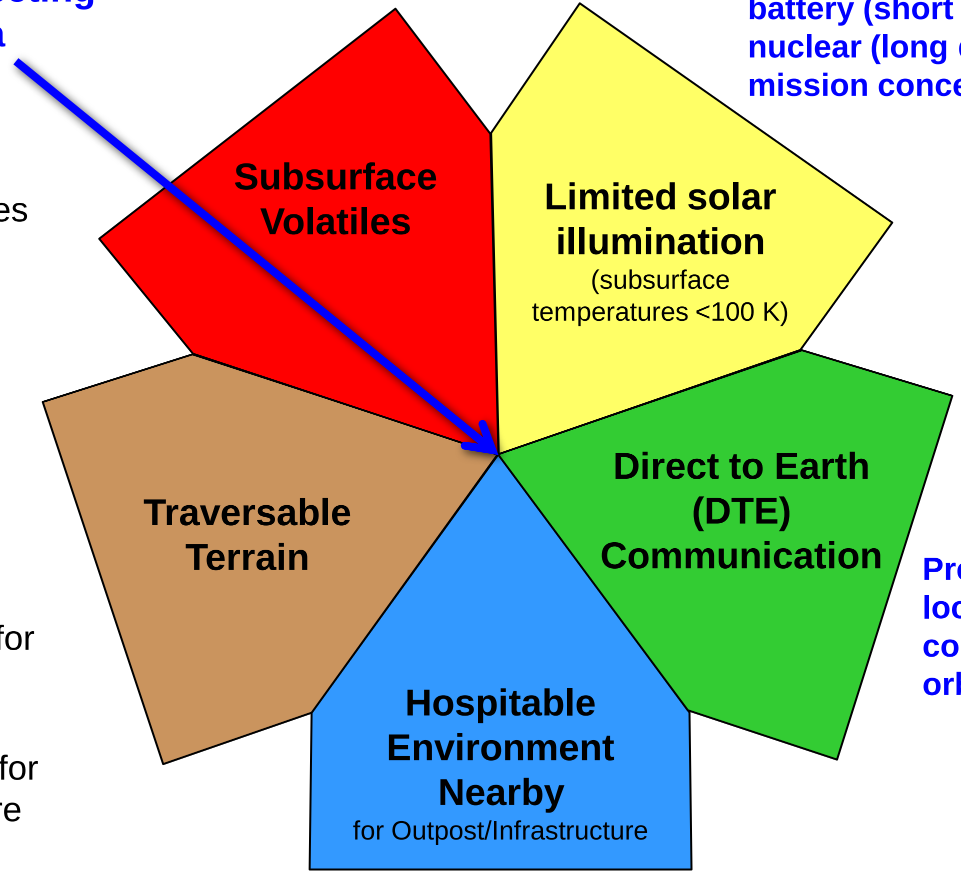
- 1,000 kg oxygen (O_2) per year for life support backup (crew of 4)
- 3,000 kg of O_2 per lunar ascent module launch from surface to L_1/L_2
- 16,000 kg of O_2 per reusable lunar lander ascent/descent vehicle to L_1/L_2 (fuel from Earth)
- 30,000 kg of O_2/Hydrogen (H_2) per reusable lunar lander to L_1/L_2 (no Earth fuel needed)

*Note: ISRU production numbers are only 1st order estimates for 4000 kg payload to/from lunar surface

Step 1 - Site Selection Criteria for Polar Volatiles Prospecting and Mining

Polar landing site based on meeting the following Five main criteria

1. Surface/Subsurface Volatiles
   - High hydrogen content (LRO LEND instrument)
   - Constant <100 K temperatures 10 cm below surface (LRO Diviner instrument)
   - Surface OH/H_2O (M^3, LRO LAMP)
2. Reasonable terrain for traverse
3. Direct view to Earth for communication
4. Sunlight for duration of mission for power generation (non-nuclear)
5. Hospitable environment nearby for mining and logistics infrastructure

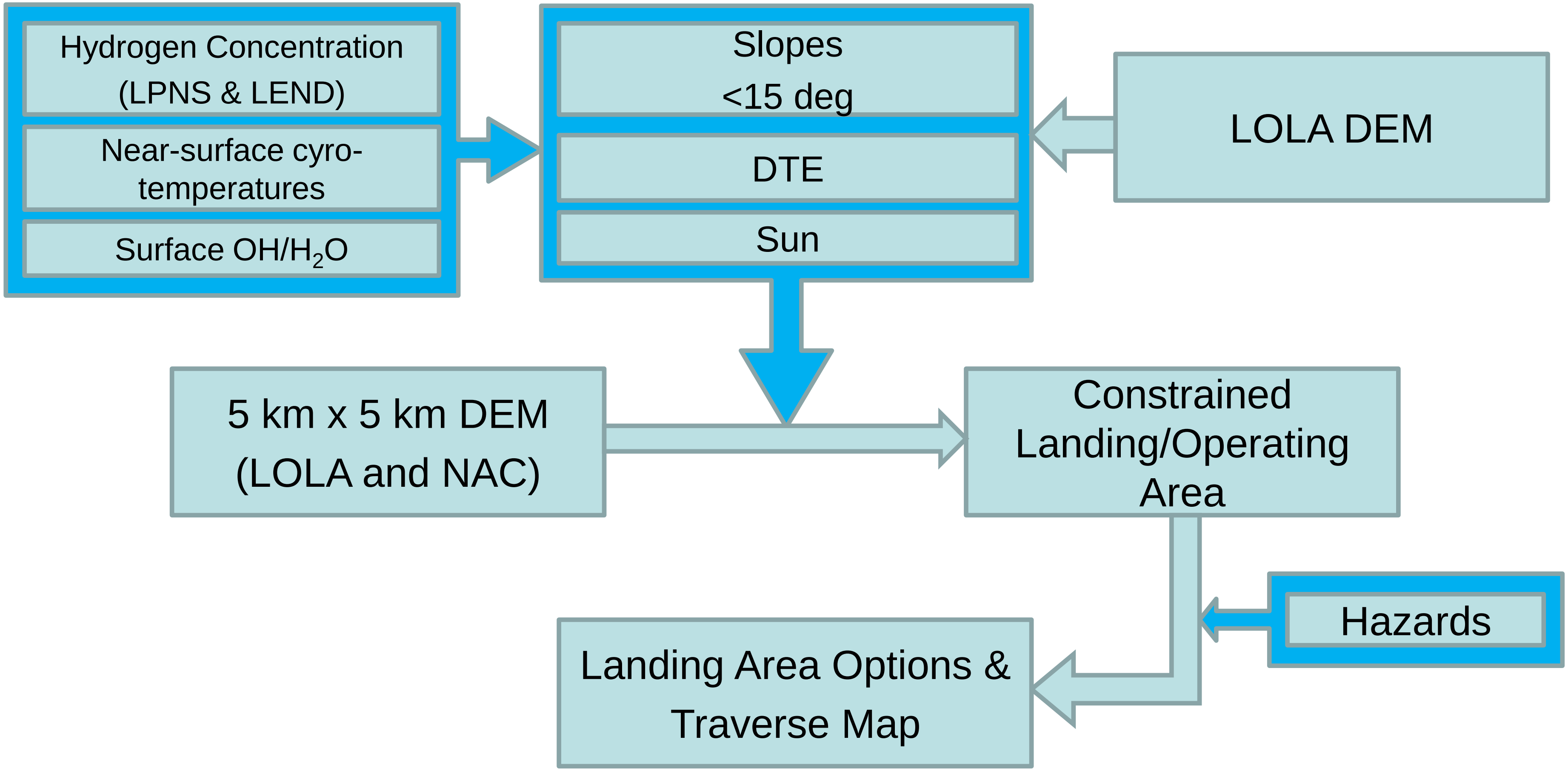


Not a site selection criteria for battery (short duration) or nuclear (long duration) science mission concepts

Prevents lunar farside locations unless a communication orbiter is available

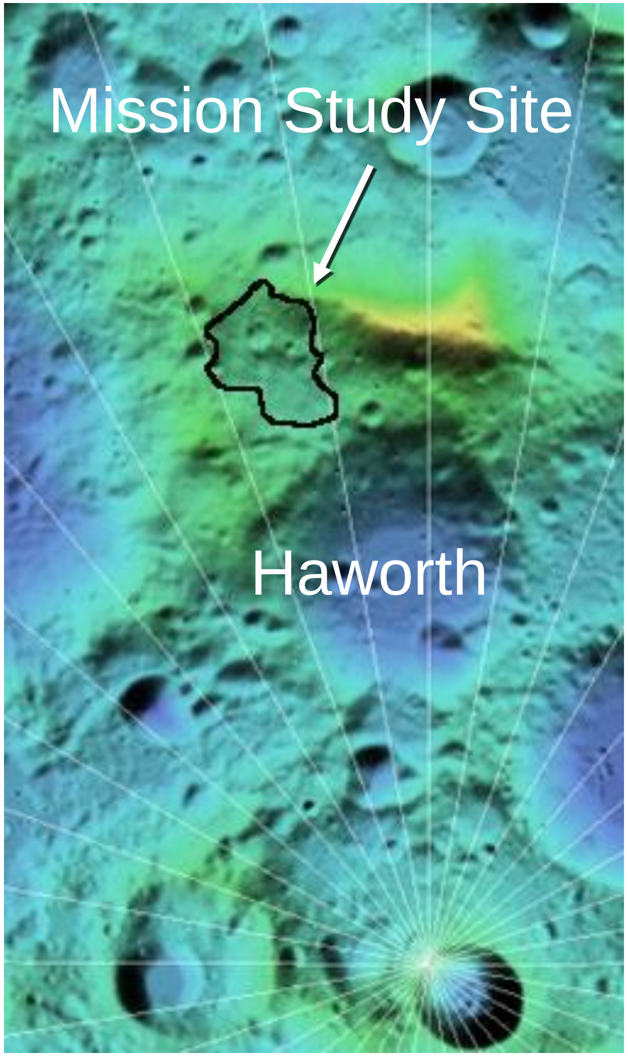
Required for long-term Mining operations

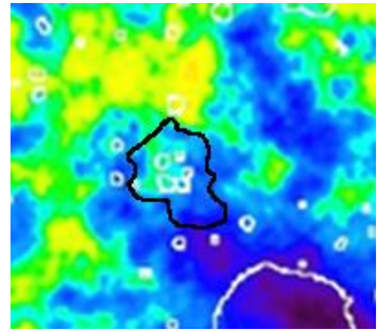
Polar Volatile Site Selection Process for Resource Prospector Mission (RPM)



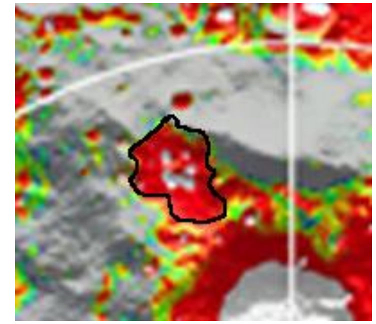
- Slopes, DTE and Sun requirements are used to mask initial 5x5km Dem to Constrained Landing/Operation Area
- Within this Constrained Area, hazards are identified via visible inspection of NAC frames and safe landing sites are identified and rover pre-planned travers mapped

Site Selection *Example* – North Haworth Study Site

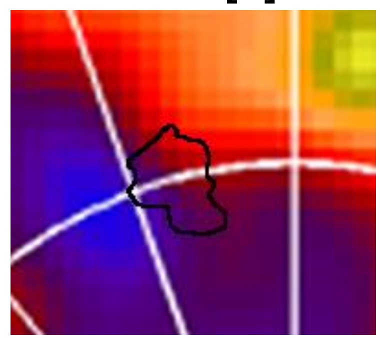




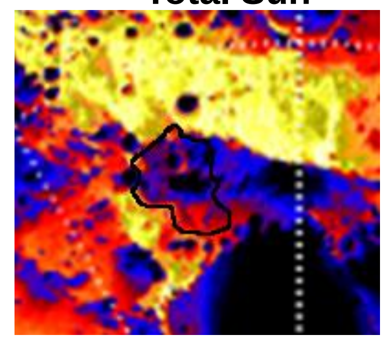
LPNS [H]



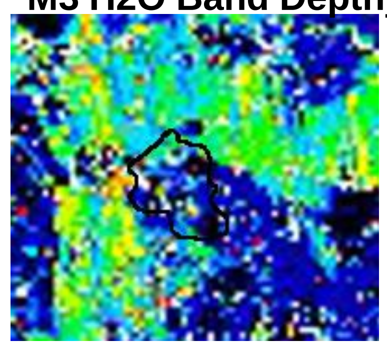
Total Sun

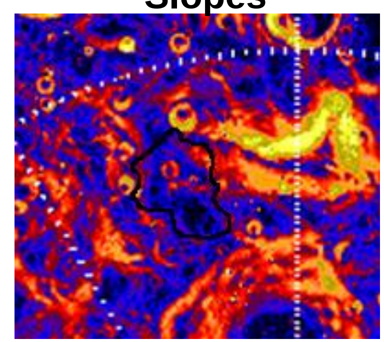


M3 H2O Band Depth]

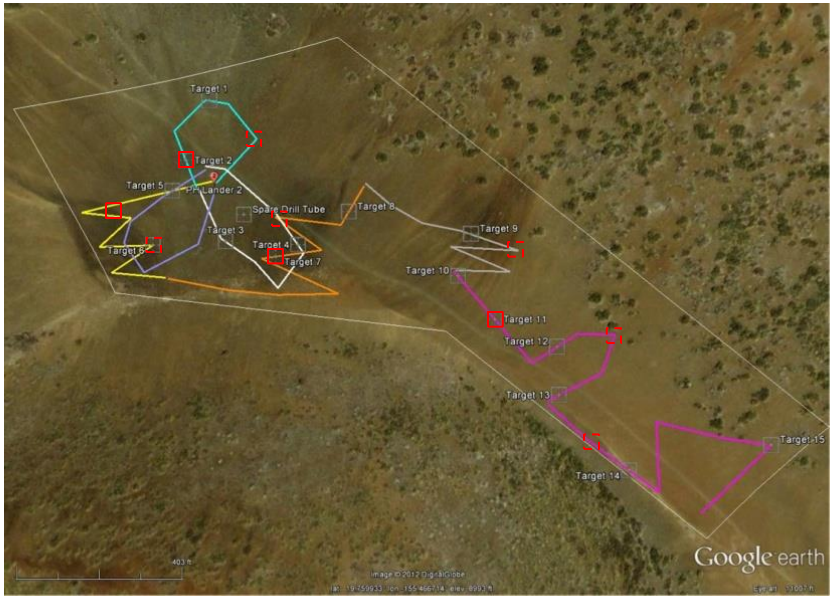


Slopes

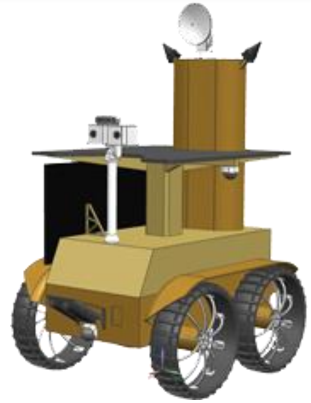




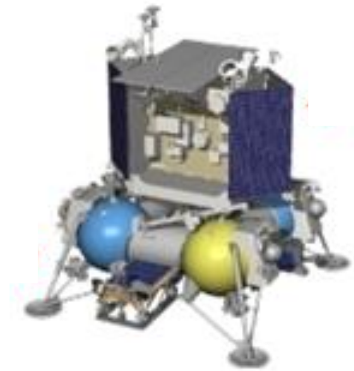
Step 2 - Exploratory Prospecting for Lunar Volatiles



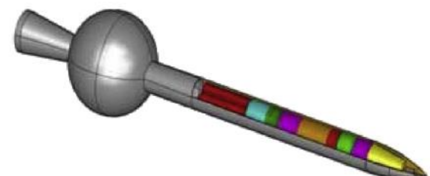
Initial traverse path based on pre-mission orbital data



Rover



Lander



Penetrators

- Hypothesize location of volatiles based global data, terrain, and geological context
- Plan surface exploration before landing/impact based on landing/impact error and/or rover capabilities
- For rover missions:
  - Utilize non-invasive surface and subsurface instruments to guide selection of sample sites; Instrument suite may be limited
  - Perform coring and volatile analysis at selected locations
  - Re-plan traverse based on accumulations of results and new hypotheses

Resource Prospector Mission (RPM) -
Mission Goals & Relevance

RPM: A mission to explore lunar polar volatiles

Resource Prospecting:

- Characterize the distribution of water and other volatiles at the lunar poles
  - Map the surface and subsurface distribution of hydrogen rich materials
  - Determine the constituents and quantities of the volatiles extracted
    - Quantify important volatiles: H_2, He, CO, CO_2, CH_4, H_2O, N_2, NH_3, H_2S, SO_2

Further Support Lunar/Planetary Science:

- Perform measurements to better understand origin and movement of polar volatiles
  - Measure surficial OH/H_2O inside and outside shadowed areas
  - Measure or provide limits on key isotope ratios, including D/H, O^{18}/O^{16}, S^{36}/S^{34}, C^{13}/C^{12}

ISRU Processing Demonstration:

- Demonstrate Volatile Extraction and the Hydrogen Reduction process to extract oxygen from lunar regolith
  - Demonstrate the hardware (e.g., oven, seals, valves) in lunar setting
  - Capture, quantify, and display the water generated

RPM Level 1 Mission Requirements

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

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

1.2 RESOLVE SHALL BE CAPABLE OF OBTAINING KNOWLEDGE ABOUT THE LUNAR SURFACE AND SUBSURFACE VOLATILES AND MATERIALS

- <u>Full Success Criteria:</u> Take <u>both</u> *sub-surface measurements of volatile constituents via excavation and processing* <u>and</u> *surface measurements*, at multiple locations
- <u>Minimum Success Criteria:</u> Take either sub-surface measurements of volatile constituents via excavation and processing or surface measurements, at multiple locations

RPM Level 2 Measurement Requirements

Paraphrased from Level 2 requirements (from SRD)

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

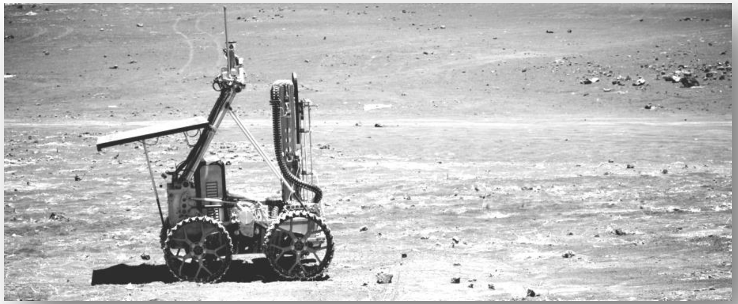
Full Success:
- Measurements from two places separated by at least 1000 meters
- Surface and subsurface measurements (auger or core)
- Measurements in and sample acquired from shadowed area
- Demonstrate Regolith Oxygen Extraction

Stretch Goals:
- Make subsurface measurements (auger) at least eight (8) locations across 1000 m (point-to-point) distance
- Make subsurface measurements (core and process) at least four (4) locations across 1000 m (point-to-point) distance
- Provide geologic context

Simplified view of Resource Prospector Mission

Get there…

- Launch
- Cruise
- Descent & Landing
- Quick Checkout
- Roll-off Lander
- Quick Checkout
- Begin Surface Ops



Find & Mine Volatiles…

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

Extract soil core — Use the Drill Subsystem to excavate up to 1[m] core sample

Heat soil — Heat samples (150degC) in the OVEN Subsystem

Determine 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)

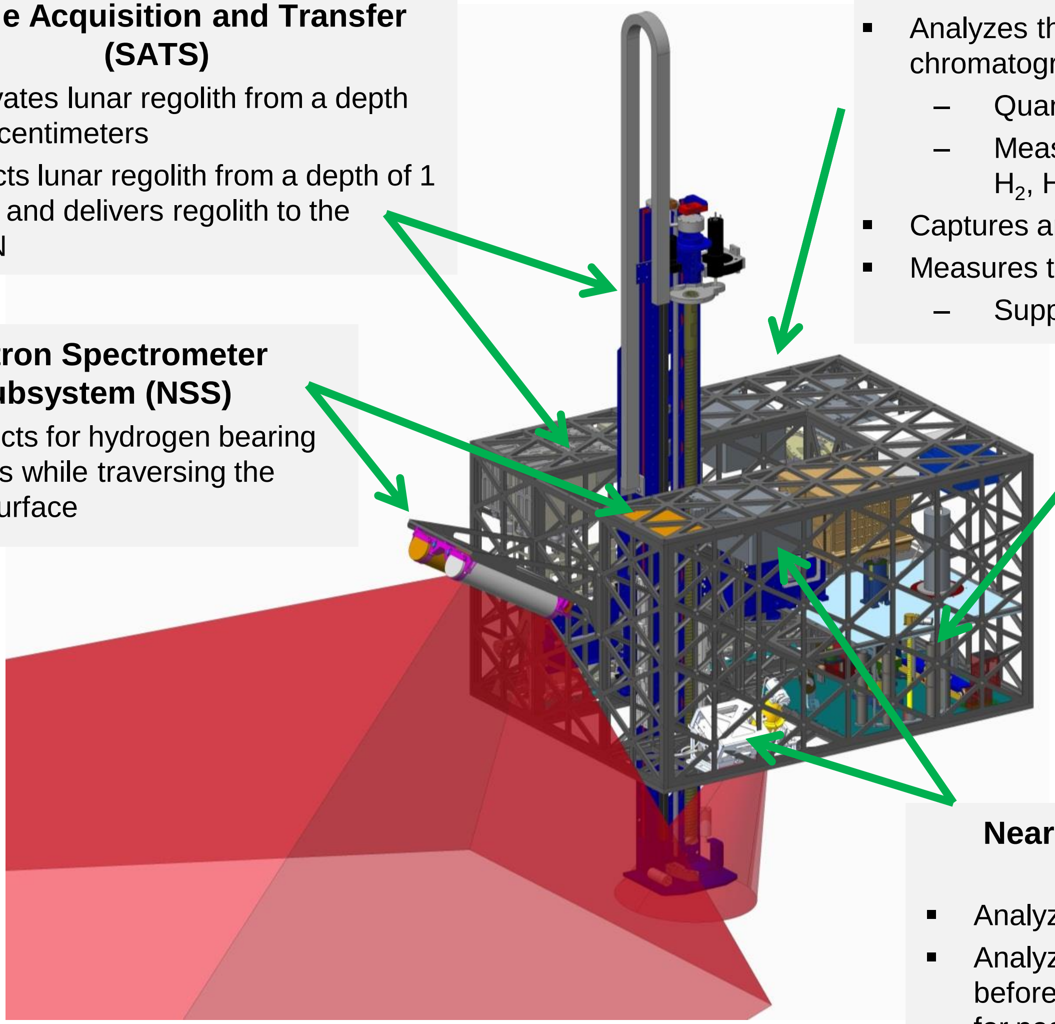
Utilize the volatiles…

Super-heat soil — Heat sample to reaction temps (150-900degC) using the OVEN Subsystem

Make water — Flow H_2 through the heated soil to capture oxygen and make water using the OVEN Subsystem

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

RESOLVE Payload for RPM



Sample Acquisition and Transfer (SATS)

- Excavates lunar regolith from a depth of 50 centimeters
- Extracts lunar regolith from a depth of 1 meter and delivers regolith to the OVEN

Neutron Spectrometer Subsystem (NSS)

- Prospects for hydrogen bearing volatiles while traversing the lunar surface

Lunar and Volatile Analysis (LAVA)

- Analyzes the evolved volatiles in OVEN using a gas chromatograph mass spectrometer (GC-MS)
  - Quantifies water content
  - Measures the relative concentrations of CO, CO_2, H_2, H_2S, NH_3, SO_2, CH_4, and C_2H_4
- Captures and images water extracted from the regolith
- Measures the water production rate during ROE
  - Supplies hydrogen for ROE

Oxygen and Volatile Extraction Node (OVEN)

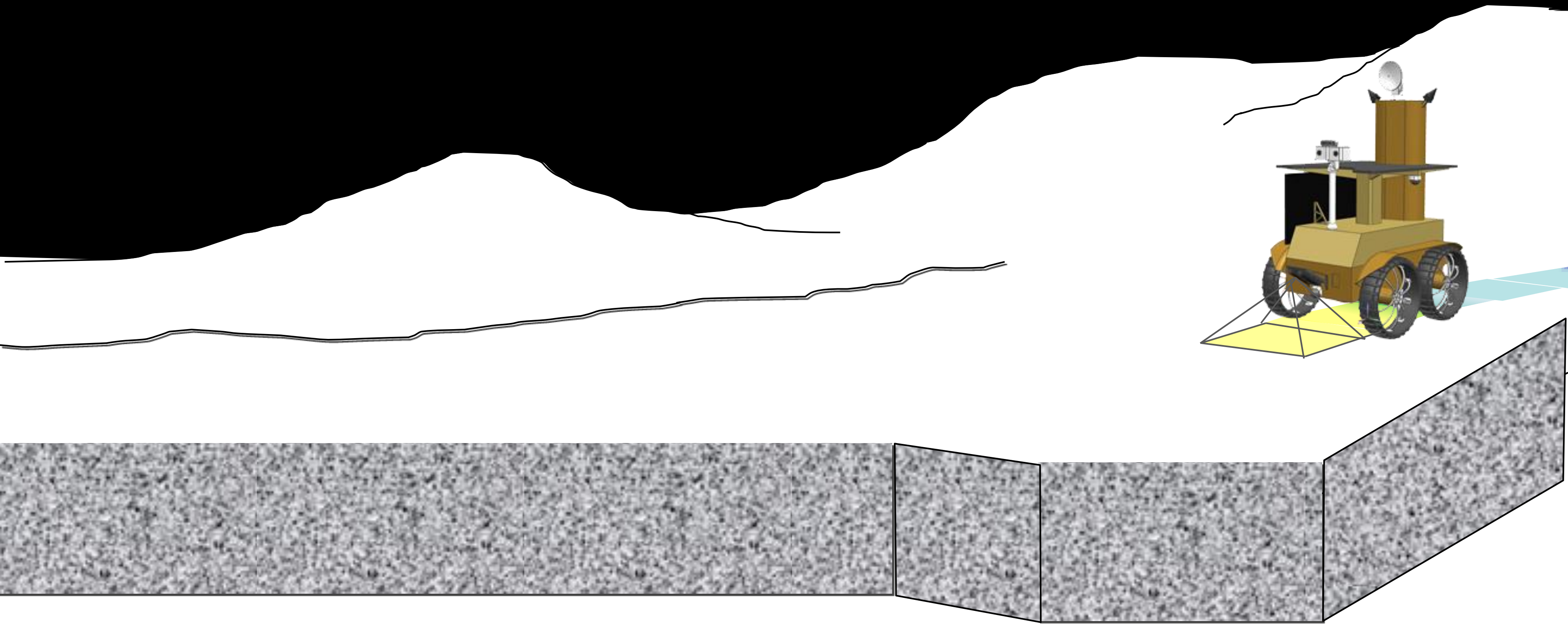
- Accepts regolith from the SATS
- Weighs the regolith
- Evolves the volatiles in a sealed chamber
- Extracts oxygen from the regolith via hydrogen reduction (ROE)

Near InfraRed Volatile Spectrometer Subsystem (NIRVSS)

- Analyzes the lunar surface while traversing
- Analyzes the immediate vicinity of the drill site before and during drill/auger operations to look for near real-time changes in the properties of the materials exposed during the drilling process

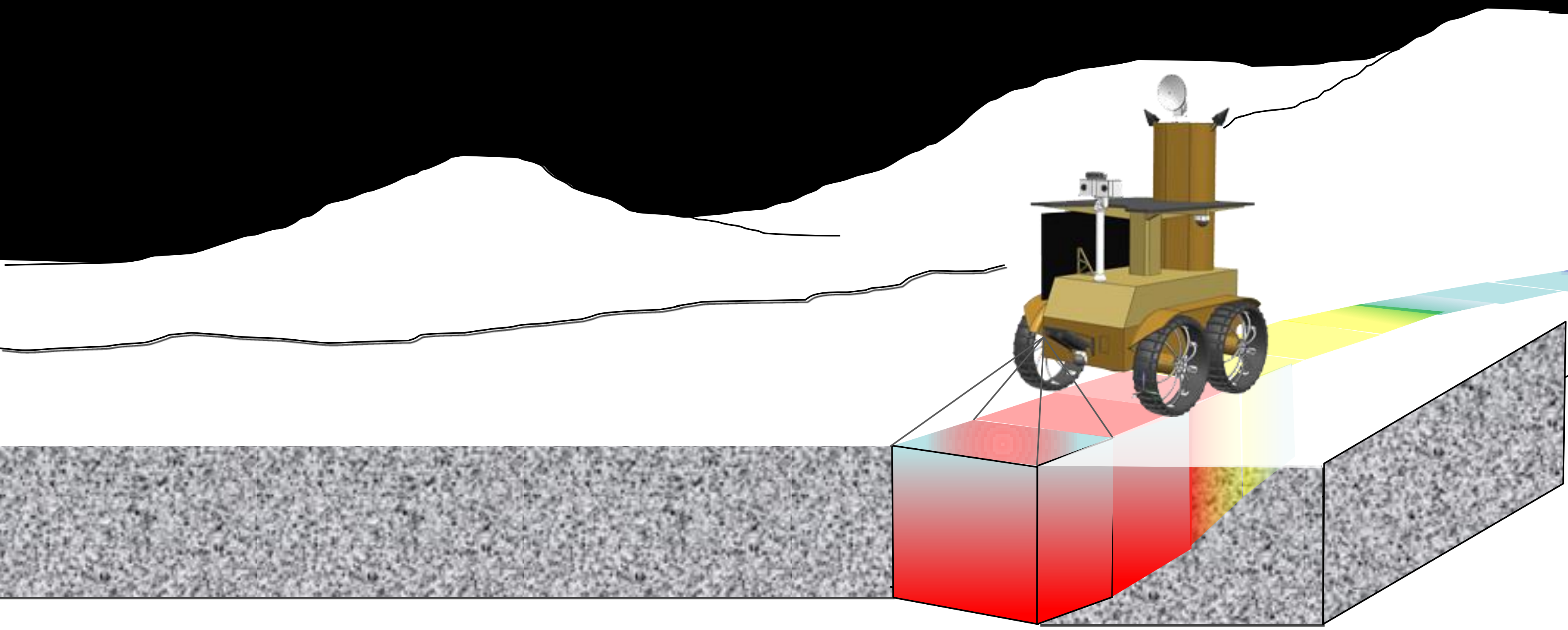
Prospecting (locating)…

1. While roving, prospecting instruments search for enhanced surface H_2O/OH, other volatiles and volumetric hydrogen



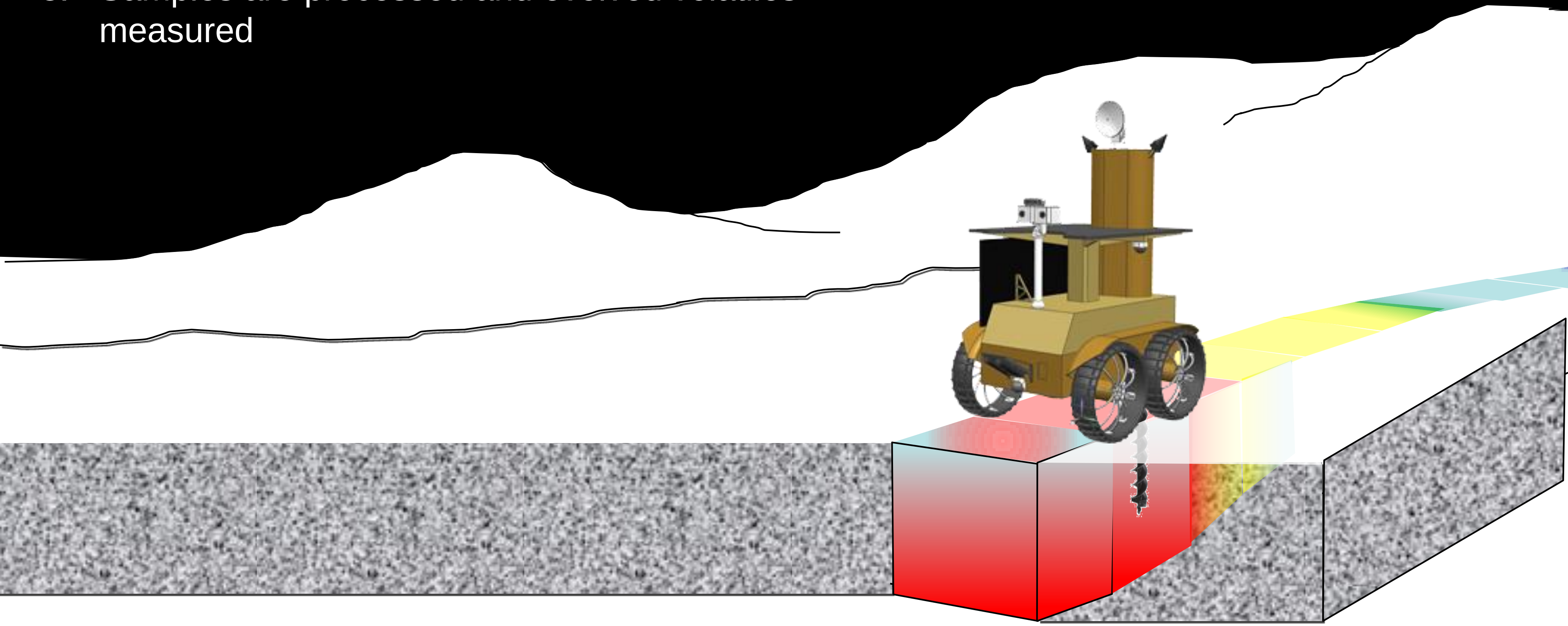
Prospecting (evaluating)…

1. While roving, prospecting instruments search for enhanced surface H_2O/OH and volumetric hydrogen
2. When enhancements are found decision made to either auger or core (sample)



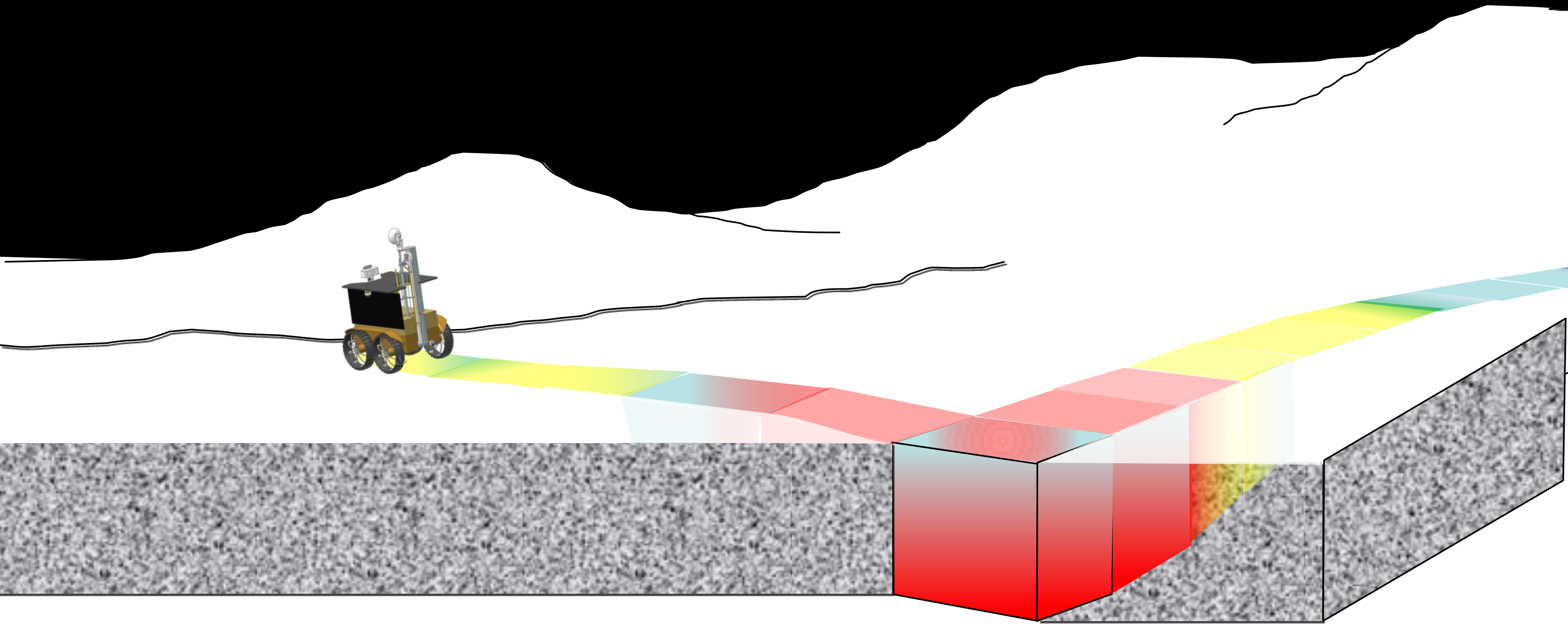
Prospecting (sampling)…

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)
3. Samples are processed and evolved volatiles measured



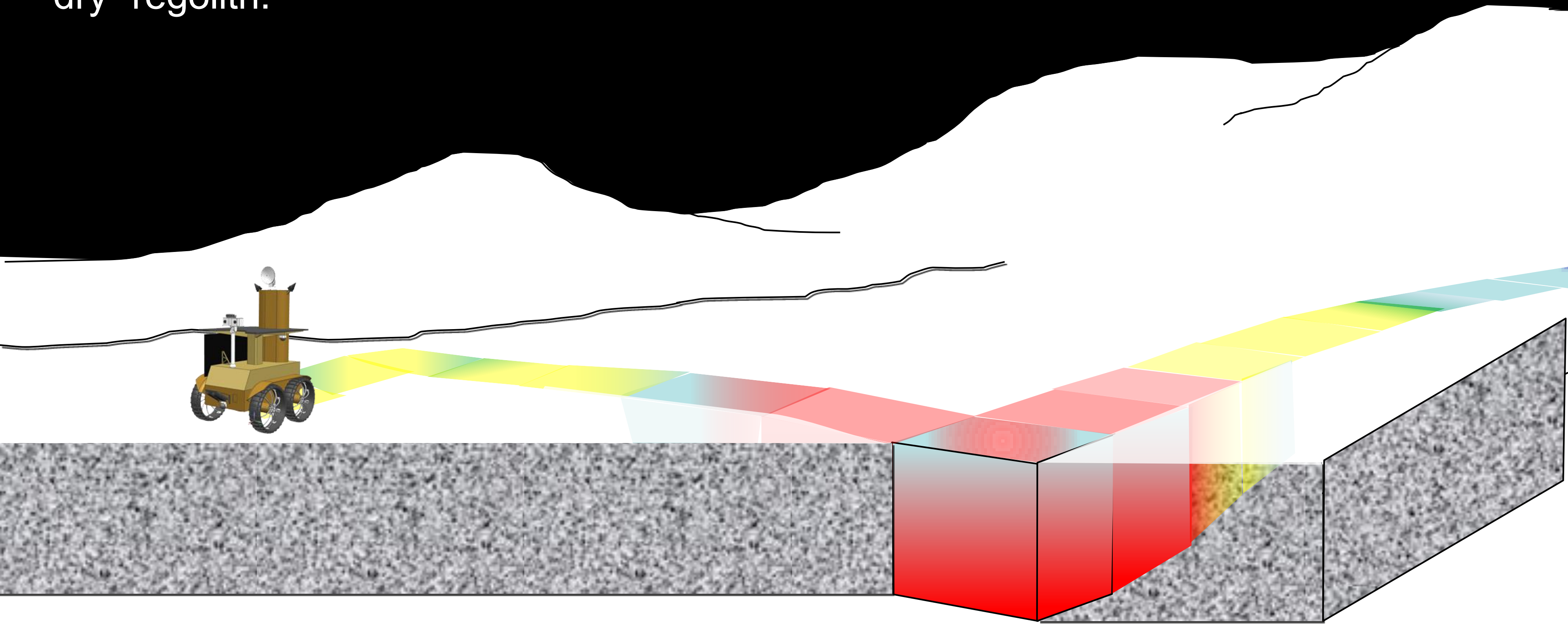
Prospecting (mapping)…

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



Demonstrating…

Concluding the primary mission, oxygen extraction from regolith with be demonstrated using hydrogen reduction, thus testing both possible ISRU pathways: local volatiles and water production from “dry” regolith.

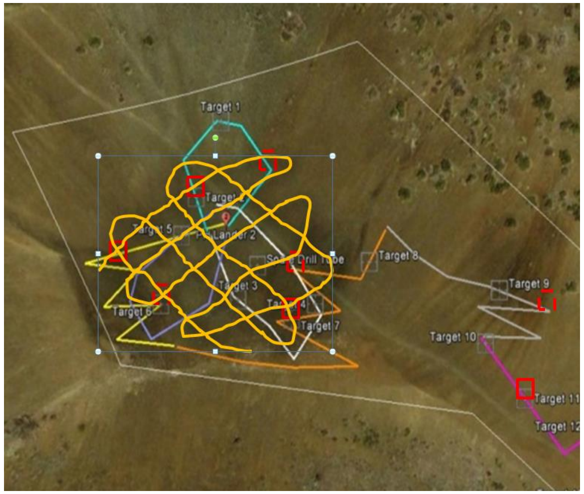


SKGs and RPM – Address at Least 22 Lunar SKGs

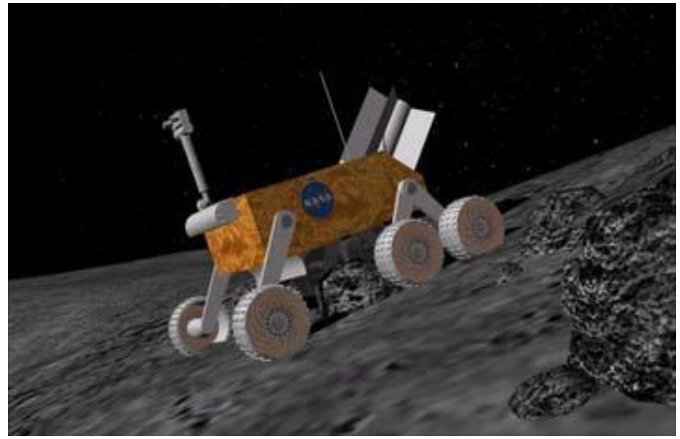
		Lunar Exploration Strategic Knowledge Gaps	Instrument or Activity	RPM Relevance
I. Understand the Lunar Resource Potential				
	B-1	Regollith 2: Quality/quanity/distribution/form of H species and other volatiles in mare and highlands	NSS, NIRVSS, OVEN-LAVA	VH
	D-3	Geotechnical characteristics of cold 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 L-M-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-ROE, 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	H
	F-4	Power Generation - Polar missions	Rover	M

VH = Very High, H = High, M = Medium, L = Low

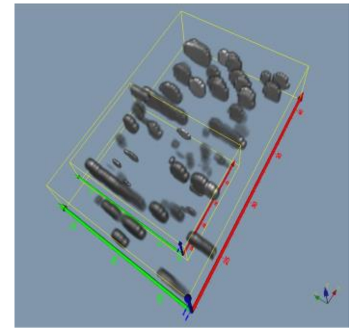
Step 3 - Focused Resource Assessment of Polar Volatiles



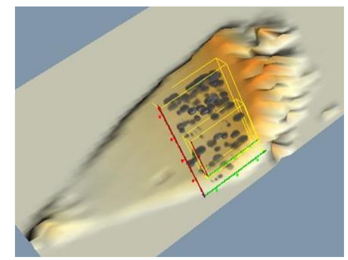
Traverse paths to fill in missing data



Long-life rover with prospecting instrument suite



Rover performs coordinated area assessment



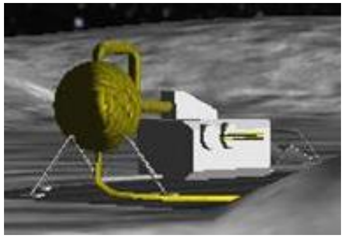
Data fusion with terrain information

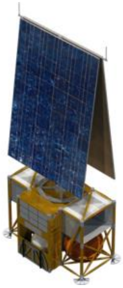
- Plan a more extensive and thorough traverse based on filling in holes in data gathered from the Exploratory Assessment; Utilize multiple rovers if possible for redundancy and greater coverage (multinational?)
- Utilize more extensive instrument suite if possible to gather greater data on both volatile location and characteristics
  - Besides NS and Near IR, potentially include GPR and more mineral/physical instruments
- Utilize more instruments to assess volatiles and potential contaminants released and condensed with water
- Build 3-D interpretation of data as it is collected; utilize to redirect traverse and data sampling activities
- Utilize extended operations to provide lessons learned for
  - Designing mining feasibility hardware
  - Establishing operation protocols and procedures for remote mining
  - Verifying communications, localization, and situational awareness

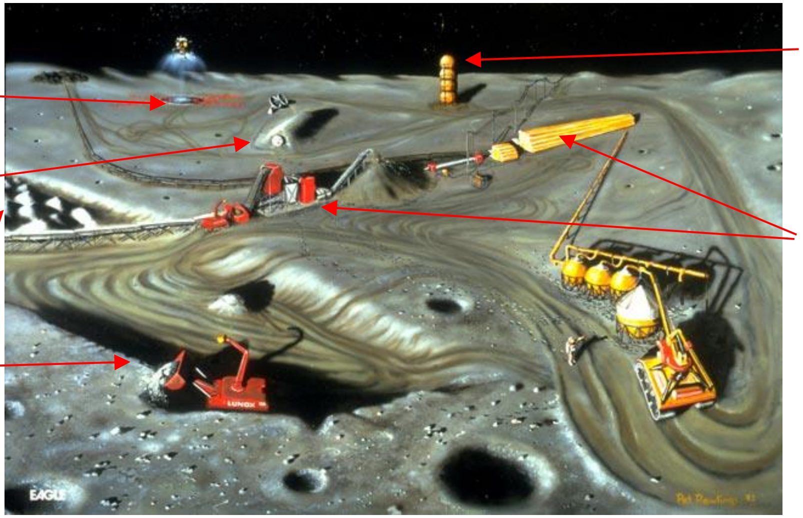
Step 4 - Mining Feasibility for Polar Volatiles

- Demonstrate critical mining and processing hardware
  - Finalize polar rover/mobility design for subsequent mining operations
  - Demonstrate ISRU hardware for sustained excavation, processing, and collection of polar water/volatiles
  - Demonstrate water cleaning, processing, and storage that can be scaled up to mining rates
  - Demonstrate fuel production from carbon-bearing volatiles if present
  - Demonstrate power system for sustained operations
- Finalize operation protocols and procedures for remote mining
- Establish mine infrastructure and operation area layout
- Establish benchmarks for logistics, mean-time between failures, etc.


Polar Mobility, Excavation & Processing


Water Plant & Product Storage


Polar Power System



Plan for Mine/Infrastructure Layout & Operation

Community Input Desired

- RPM – Step 2 Exploratory Prospecting.
  - Do the Level 1 and Level 2 Mission requirements for RPM meet the intent for lunar volatile prospecting and ISRU?
  - Are the RPM instruments and mission duration sufficient for initial Exploratory Prospecting mission needs?
- If PRM is successful, what is the Best Approach to proceed to Step 3 and beyond?
  - Are other Exploratory missions required before proceeding? Luna 27, ???