National Aeronautics and Space Administration

Resource Prospector: Evaluating the ISRU Potential of the Lunar Poles

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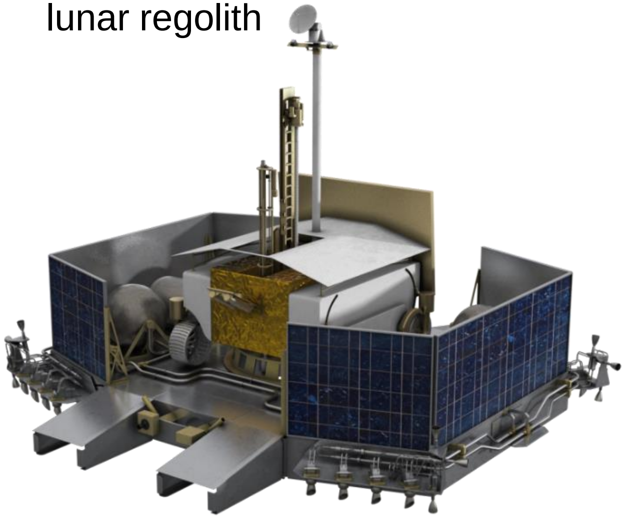
LEAG

2016-11-02

Resource Prospector (RP) Overview

Mission:

- Characterize the nature and distribution of water/volatiles in lunar polar sub-surface materials
- Demonstrate ISRU processing of lunar regolith



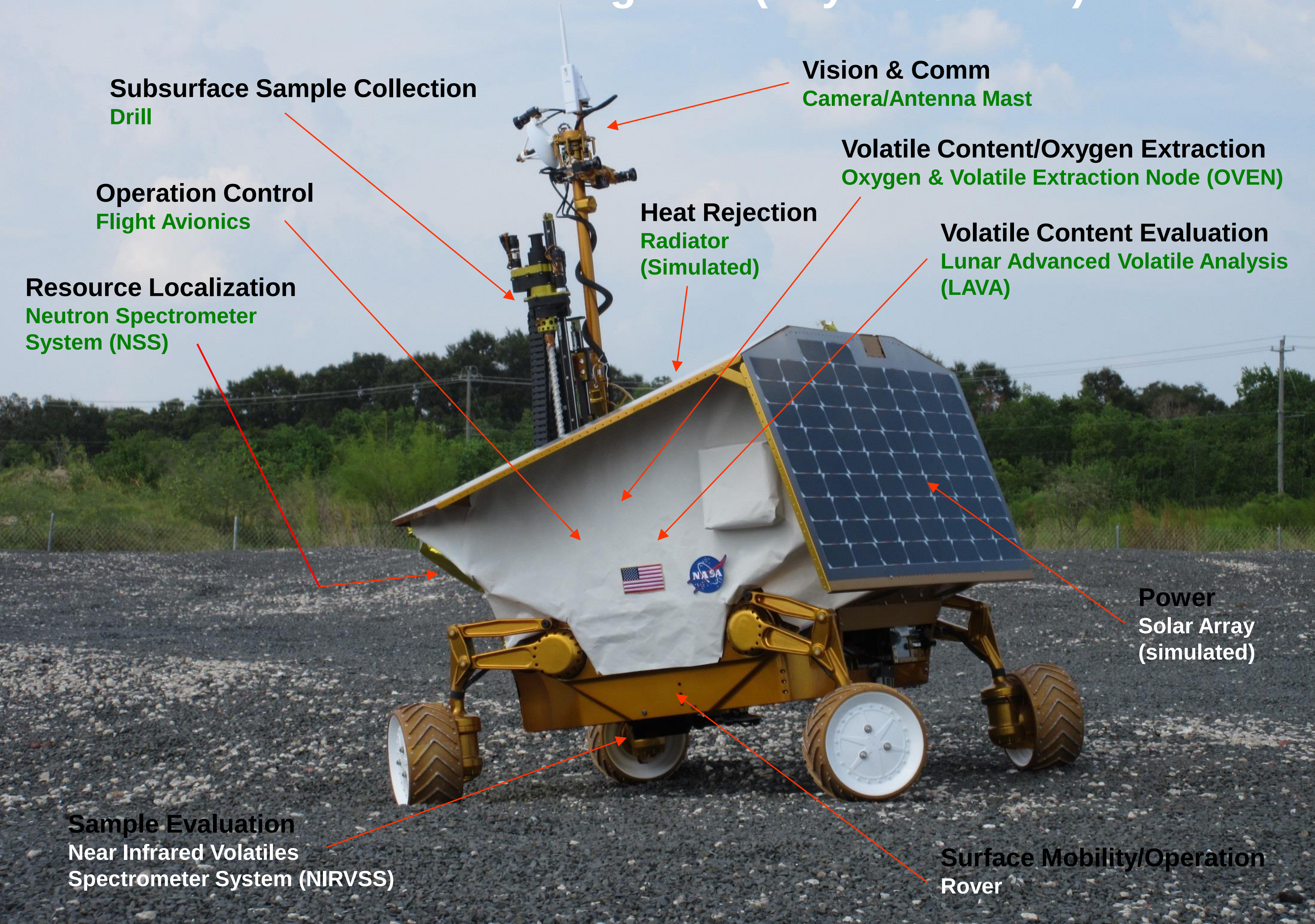
Project Timeline:

- ✓ FY13: Pre-Phase A: MCR (Pre-Formulation)
- ✓ FY14: Phase A (Formulation)
- ✓ FY15: Phase A (Demonstration: RP15)
- ✓ FY16: Phase A (Risk Reduction)
- FY17: Baseline design; SRR/MDR
- FY18: PDR (Implementation)
- FY19: CDR (Critical design)
- FY20: I&T
- FY21: RP launch

RP Specs:

Mission Life: 6-14 earth days
(extended missions being studied)
Rover + Payload Mass: 300 kg
Total system wet mass (on LV): 5000 kg
Rover Dimensions: 1.4m x 1.4m x 2m
Rover Power (nom): 300W
Customer: HEOMD/AES
Cost: ~$250M (excl LV)
Mission Class: D-Cat3
Launch Vehicle: Falcon 9 v1.1

RP15: Surface Segment (Payload/Rover)



Partnerships & Demonstrations

RP working three simultaneous tracks

2015 → 2016 →

NASA-International partnerships — Taiwan & JAXA — 2021+

Work partnerships for "Full-up" RP with 300kg Prospecting & ISRU Payload and Rover system

NASA-Commercial partnerships — 2017/2018

Market research of NewSpace commercial options for RP

Per AES PPBE18 PRG: Investigate early commercial flight opportunities for RP instruments

RP15 → **RP15** — 2016

Build a "RP15" prototype rover/payload system ("Surface Segment")

"RP15" Surface Segment analogue and environmental testing

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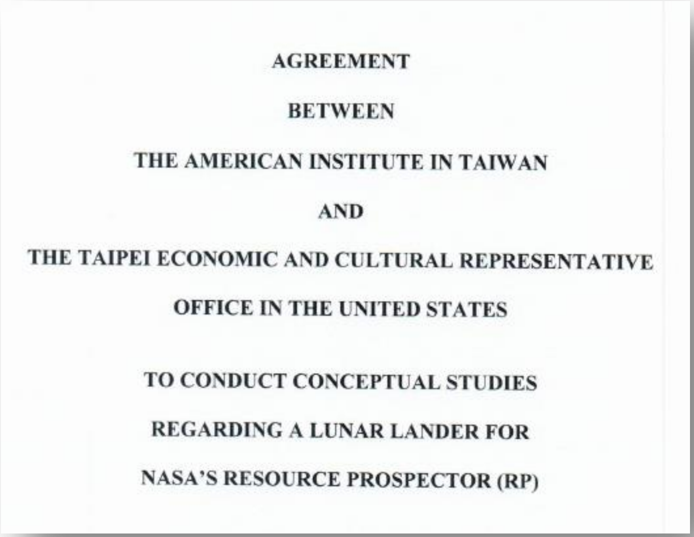
International Partnerships

- <u>Taiwan:</u> 6-mo Study agreement (Jan-July 2016); Extending +1yr to July 2017 to work flight agreement
- <u>Taiwan:</u> Five Face-to-Face meetings to date: 2015-07: Taipei, TW, 2016-02: MSFC, AL, 2016-04: Taipei, TW, 2016-06: ARC, CA, 2016-09: Taipei, TW *(CFS training)*
- <u>JAXA:</u> Joint agreement was extended through March 2017, following completion of a joint study report; scope is simply landing site studies


AGREEMENT

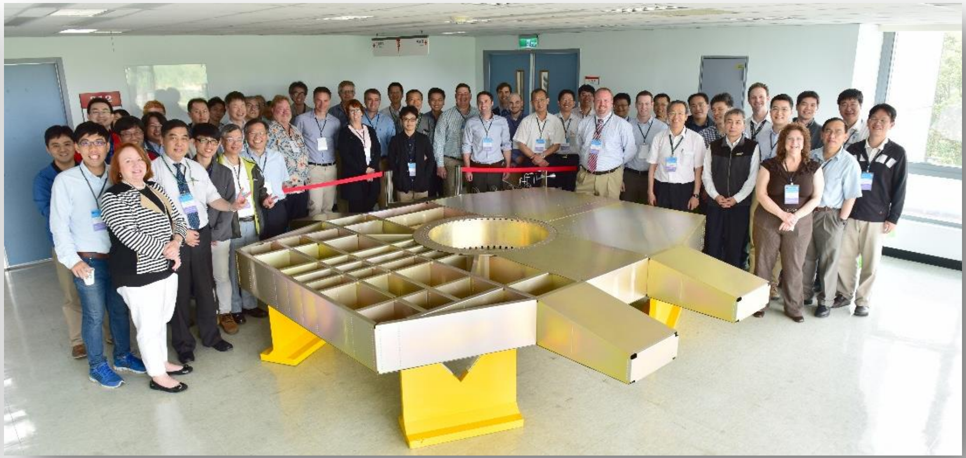
BETWEEN

THE AMERICAN INSTITUTE IN TAIWAN

AND

THE TAIPEI ECONOMIC AND CULTURAL REPRESENTATIVE OFFICE IN THE UNITED STATES

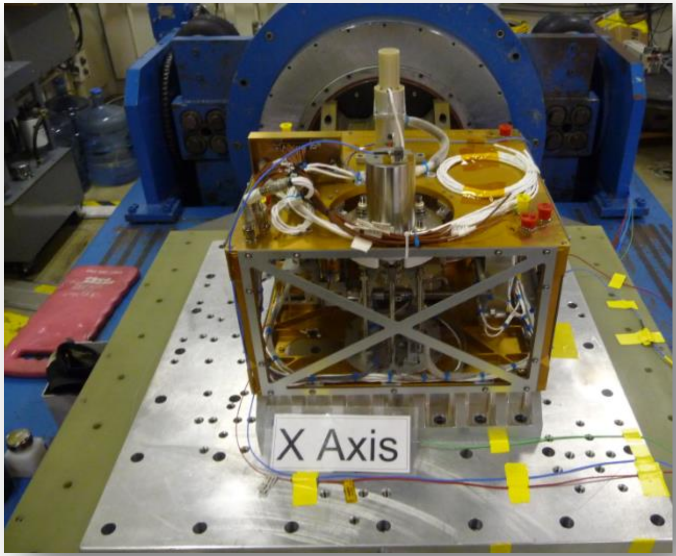
TO CONDUCT CONCEPTUAL STUDIES REGARDING A LUNAR LANDER FOR NASA'S RESOURCE PROSPECTOR (RP)



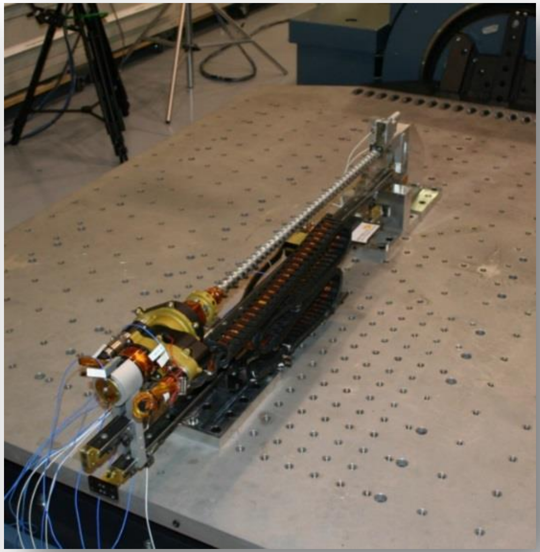
NASA-MSFC, USA

NSPO, Taiwan

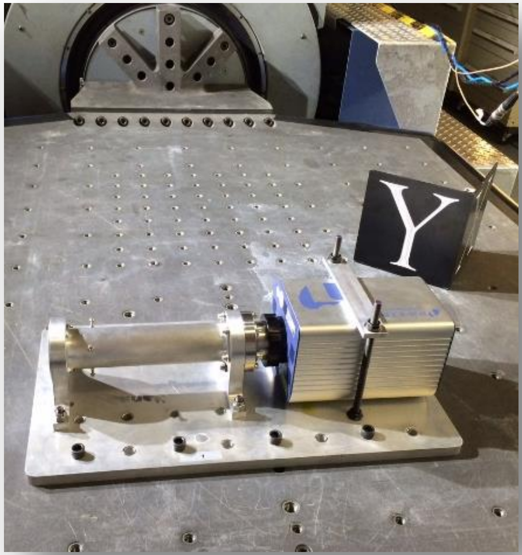
RP Payload Subsystems Environment Testing



OVEN Subsystem vibe (JSC)



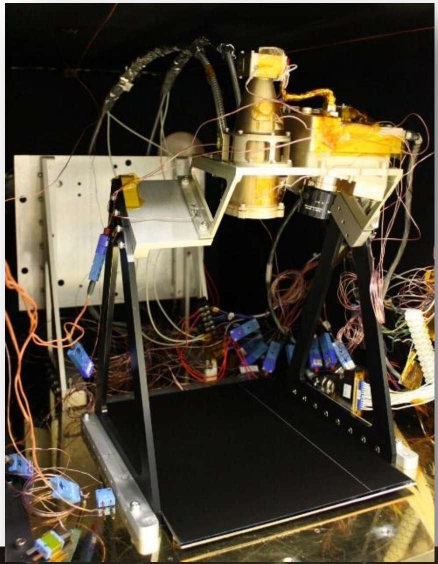
Honeybee Drill vibe(KSC)



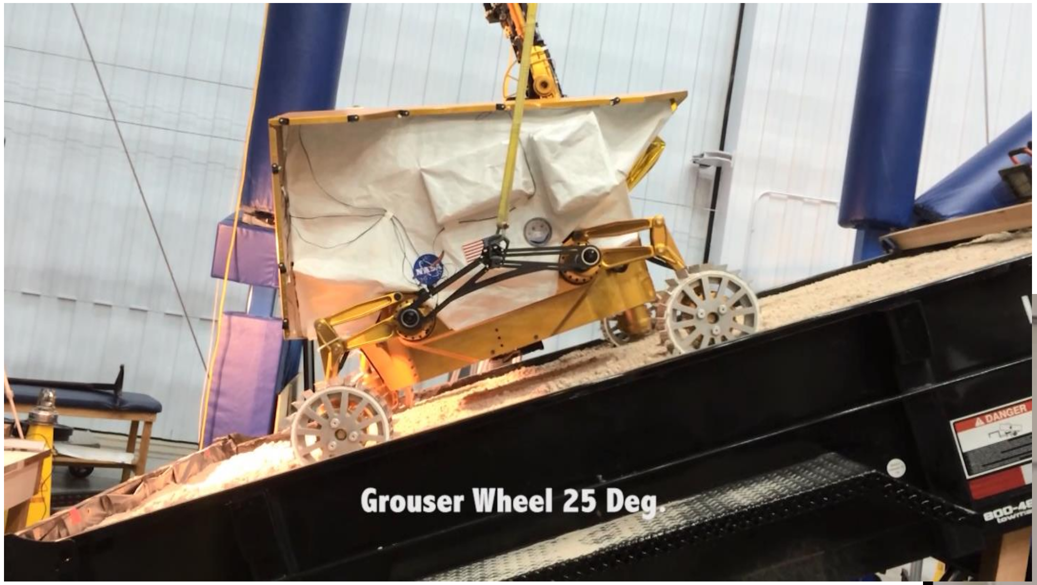
LAVA Mass Spec vibe (KSC)

ROVER w/OVEN & Drill vibe (JSC)

NIRVSS in TVAC



RP15 Rover Testing



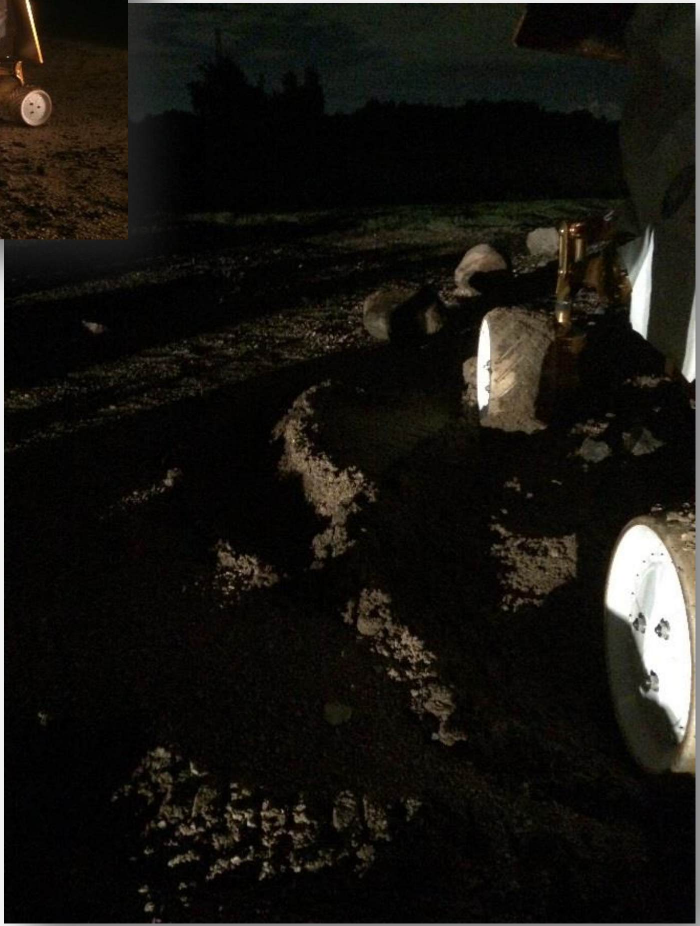
Wheel grouser studies: Obstacle climbing @ 1/6g in the ARGOS gravity offload facility

Surface Segment random vibe testing (Rover + OVEN + Drill)

RP15 wheels & steering assemblies undergoing TVAC test

Rover Night Driving : Things that go Bump In the Night?

Studying impacts of the poor lighting and long shadows in polar regions



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Rover Tiger Team Review (TTR)

- Convened a killer review team to look at the existing RP15 design and evaluate Class D sensibilities and risk
- Attendees (8): from outside the project: JPL, GSFC, ARC, UoMaryland, UCF, UoOklahoma
- Expertise: Class D, Low-cost systems, Rover driving, Mobility, Fault Management, Thermal, Flight SE
- Report Complete: 2016-04-15

Fantastic results. Reviewers applauded the RP15 accomplishment, but concerned about rover sophistication (Cost-risk)

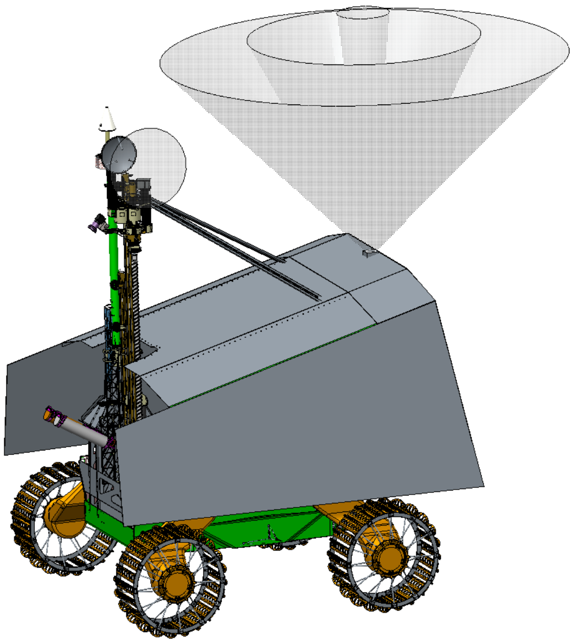
Rover team embarked on a fresh "AoA-2" study, looking to mobility simplification; L2 reqs were made negotiable to explore options

Rover AoA2 Minimum Mission Activities

Rover AoA2 activity considered a minimal mission design

- One outcome is to understand the sensitivity of key implementation options on cost and complexity
- Adopted a subset of L2 requirements, but many were negotiable
- Followed with two Independent Cost Estimates to evaluate cost/risk relationship for various subsystems

AoA2 Rover Concept



Pushed hard to the "minimum" set of requirements

- Two measurements in sun, separated by 100 meters, one measurement in PSR

➢ ***Ultimately wanted to reconcile the current L2s, AoA2 adopted L2s with the L1s and the customer's intentions***

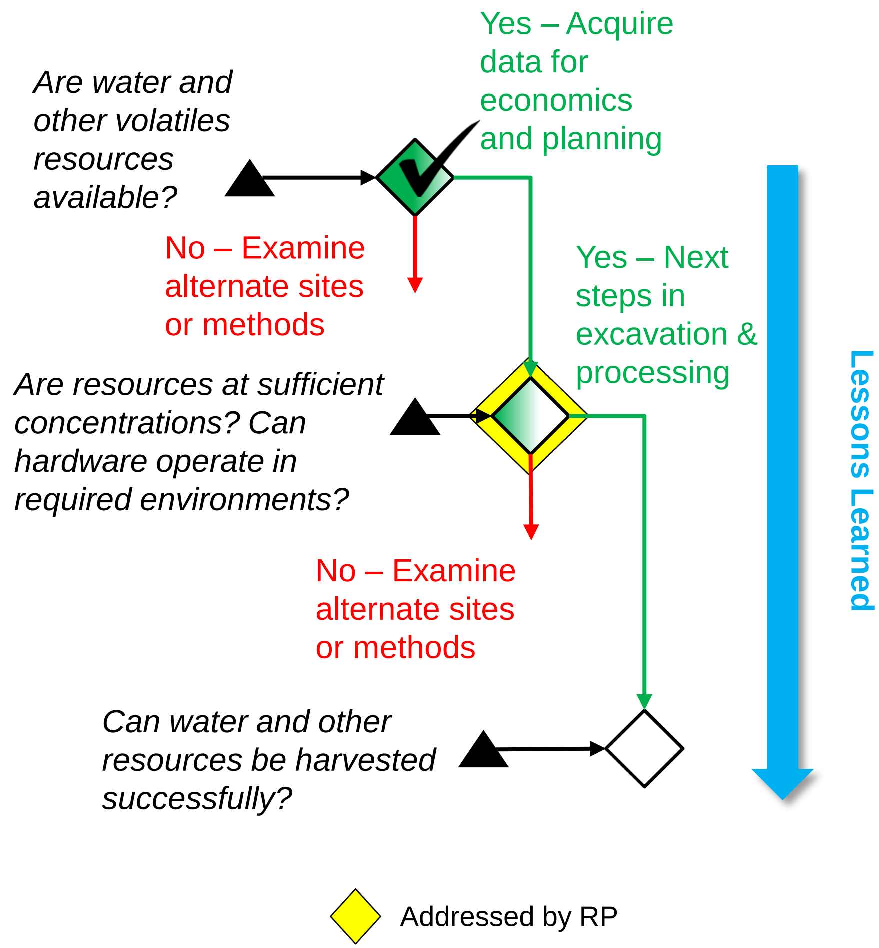
What is the Lunar Polar ISRU Potential?

Important Parameters for ISRU Viability / Economics

- Volatile distribution (concentration, including lateral and vertical extent and variability)
- Volatile Form (H_2, OH, H_2O, CO_2, Ice vs bound, etc).
- Overburden: How much material needs to be removed to get to ore?
- Working Environment: Sun/Shadow fraction, soil mechanics, trafficability, temperatures

Resource extraction must be 'Economical'

- Need data concerning distribution and accessibility to help determine if a resource and processing technique allows for positive Return on Investment (ROI), including Mass, Cost, Time, and Mission/Crew Safety
- Amount of product needed justifies investment in extraction and processing



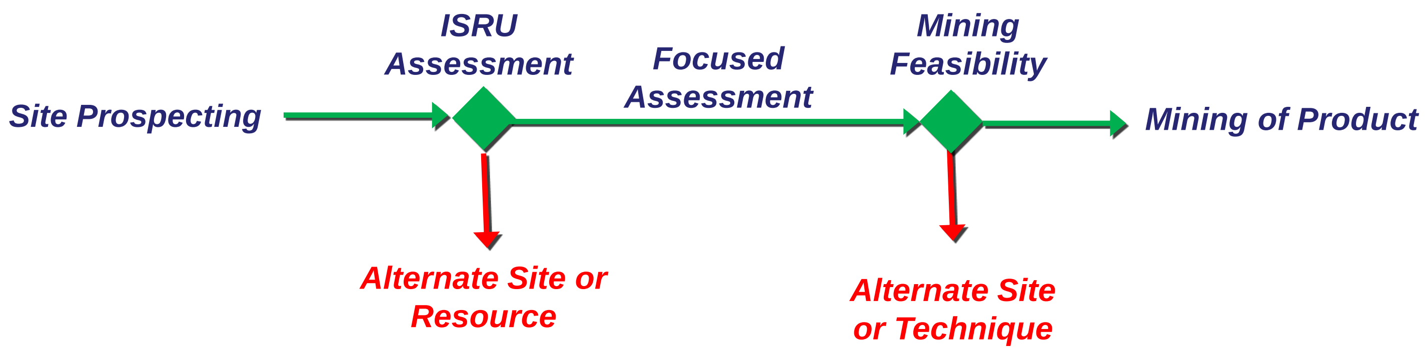
Addressing the ISRU Potential

Measurements should:

- Provide enough information to allow for the next step: e.g., excavation and pilot processing plant demonstration

- Provide ground truth for models and orbital data sets, including:
  - Temperatures at small scales, subsurface temperatures and regolith densities
  - Surface hydration
  - Hazards (rocks and slopes)

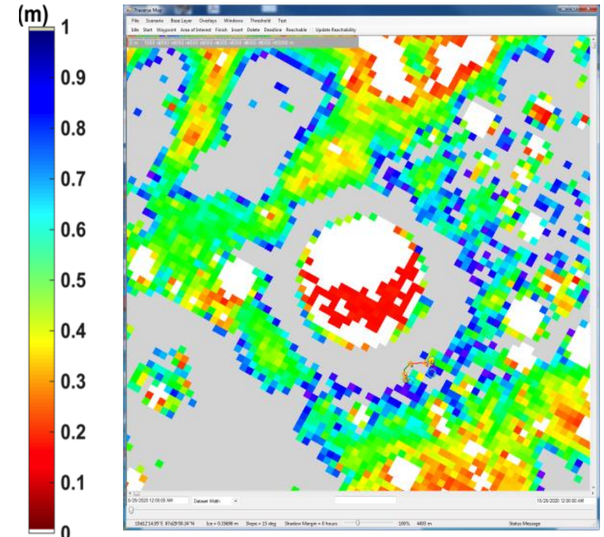
- Address key hypothesis regarding polar volatile sources and sinks, retention and distribution, key to developing economic models and identifying excavation sites



What is the ISRU value of deposits across the range of environments or terrain types?

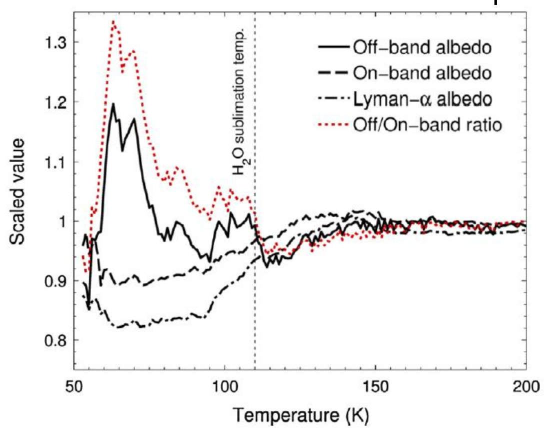
- Need to provide strategic knowledge input to the resource potential / economics: *In what environment is the ISRU potential maximum?*
- What is the volatile concentration across a working area, for example an excavation area of 50x50m?
- Defined four environments based on the thermal stability of ice:
  - **Dry**: Temperatures in the top meter expected to be too warm for ice to be stable
  - **Deep**: Ice expected to be stable between 50-100 cm of the surface
  - **Shallow**: Ice expected to be stable within 50cm of surface
  - **Surface**: Ice expected to be stable at the surface (ie., within a Permanently Shadowed Region, PSR)

Thermal Ice Stability Depth Map



Siegler et al., 2016

LAMP Reflectance vs Surf. Temp.



Hayne et al., 2016

RP Measurement Requirements

Goal: Identify ISRU potential of an area at least 50x50m in each of the four thermal environments

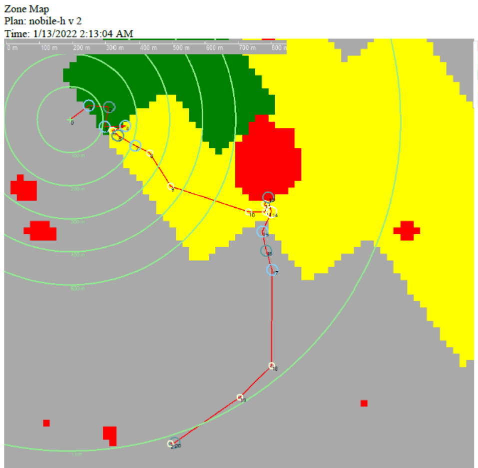
- Measurements must discern "representative" concentration of volatiles (hydrogen) across "excavation site" (50x50m) and with depth

Measurements:

- Determine ISRU value across all 4 thermal environments
- Prioritization given to PSR and Deep or Shallow
- Minimum of three measurements (two and a 'tie-breaker') in each environment separated by 10s of meters to account for likely heterogeneity, guided by NSS (not random selection)
- Vertical measurements must discern vertical overburden and volatile form and concentration

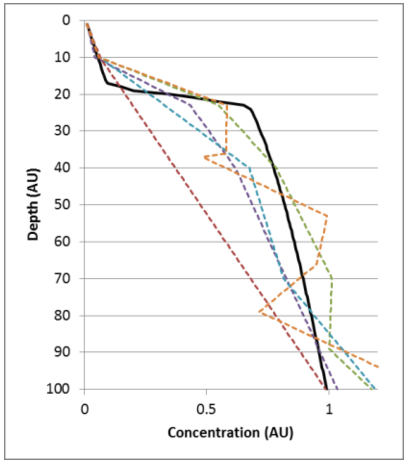
Extended:

- More measurements from additional, similar environments to further assess how representative any set of three measurements are of one particular environment
- Additional measurements from other terrain types, or to test specific hypothesis (e.g., areas in which water ice is predicted to be stable across a broader history of the Moon)



Thermal Environments

13 cm segment length
2, 3, 4,5, 7 segments



Summary

- RP continues to mature its mission concept, hardware and CONOPS
- FY16 saw a range of hardware testing, including rover and payload functional and environmental testing
- Rover AoA2 Study lead to a solidification of the mission goals and approach
- Studies continue with international partners, including a Taiwan/NASA Lander partnership and JAXA/NASA landing site analysis
- Continue to develop new tools and data sets for traverse planning (see talk by Elphic et al.)
- Looking forward to a SRR/MDR late next year!

Let’s go….

Backup

RP Level 1 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
- **Minimum Success Criteria:** Land at a polar location that maximizes the potential for obtaining a high volatile (hydrogen) concentration signature

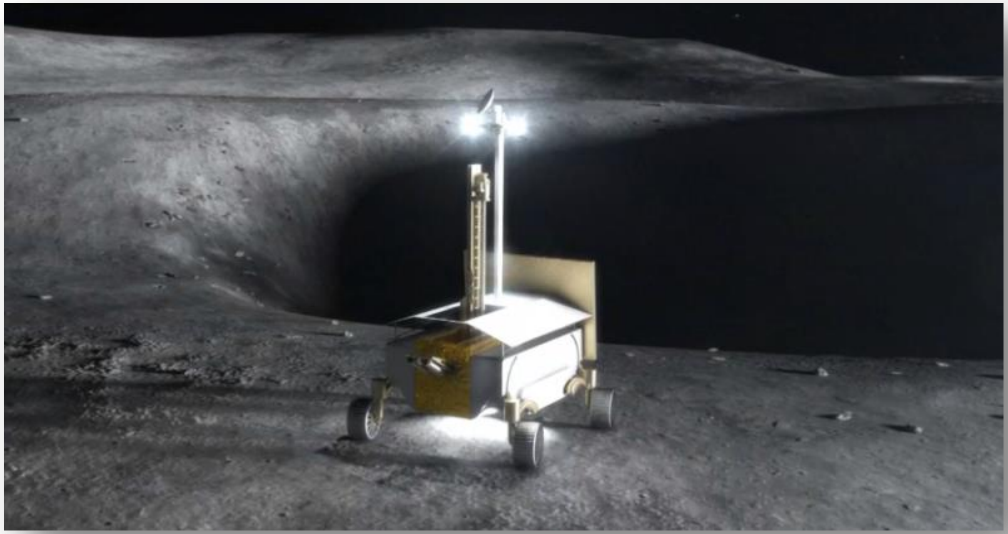
1.2 RESOURCE PROSPECTOR SHALL BE CAPABLE OF OBTAINING KNOWLEDGE ABOUT THE LUNAR SURFACE AND SUBSURFACE VOLATILES AND MATERIALS

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

Provide Data on How to Work in Polar Regions

Roving

- Traversing in soft soil; Slippage or Burial
- Sharp thermal gradients across rover and variable thermal interface with surface



Navigation

- Performance of passive imaging for hazard detection and localization
- Performance of active illumination (flood lighting and laser projection)
- Positive and negative obstacles (size, shape, distribution, composition)
- Hazard / obstacle distributions at scales of ~10 cm

Drilling

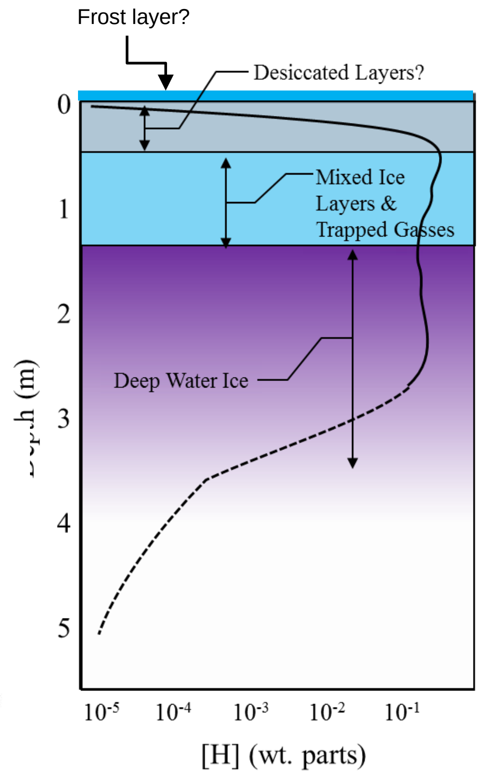
- Understand rover/drill interactions on under lunar loading and slopes
- Force on bit; Slip/unintended motion
- Stances during drilling / stuck drill and options for stuck drill recovery
- Unknown near-surface regolith compaction profile / pre-load requirements

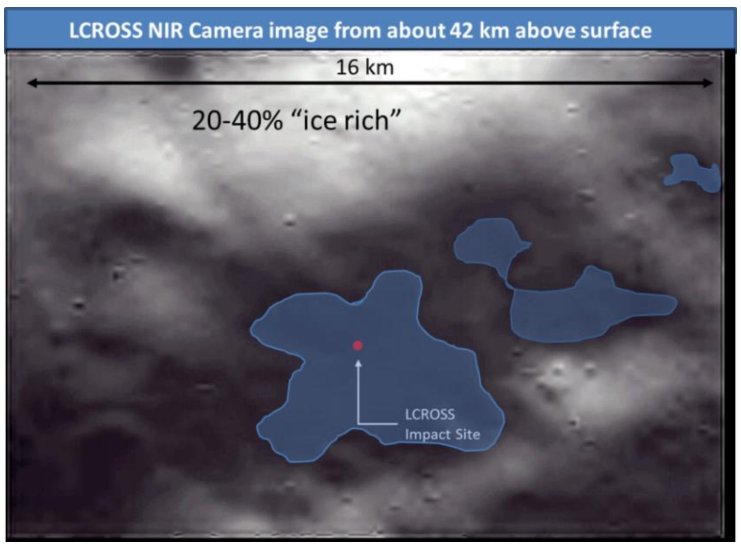
Planning and Operations

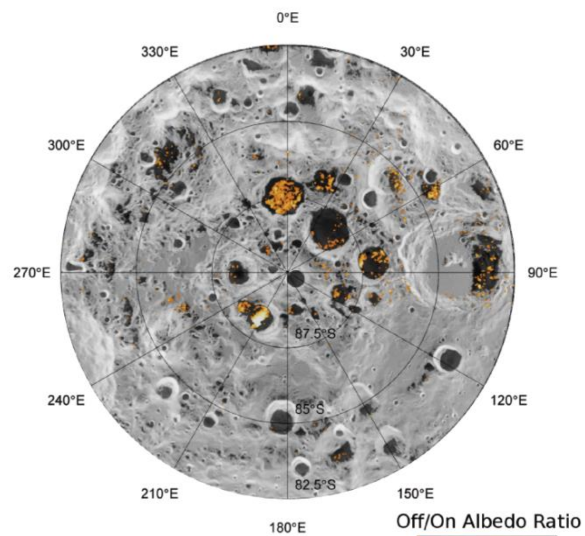
- "Real-time" operations with 10-30 sec DTE latency (light travel time and DSN catalog network latency)
- Chasing the sun and comm vs designing missions to survive extended LOS or lunar night
- Uncertainties in DTMs and impact on planning

Where to Dig for Ice?

- Data from LRO, LCROSS, and M3 suggest patchy and/or buried distributions of hydrogen
- Impact gardening will create heterogeneity at lengths scale of ~10-100s m
- Several data sets suggest potential different reservoirs, including near surface and buried
- In areas of limited sun, near sub-surface temperatures are cold enough to retain water ice for geologic timescales







Hayne et al., 2015

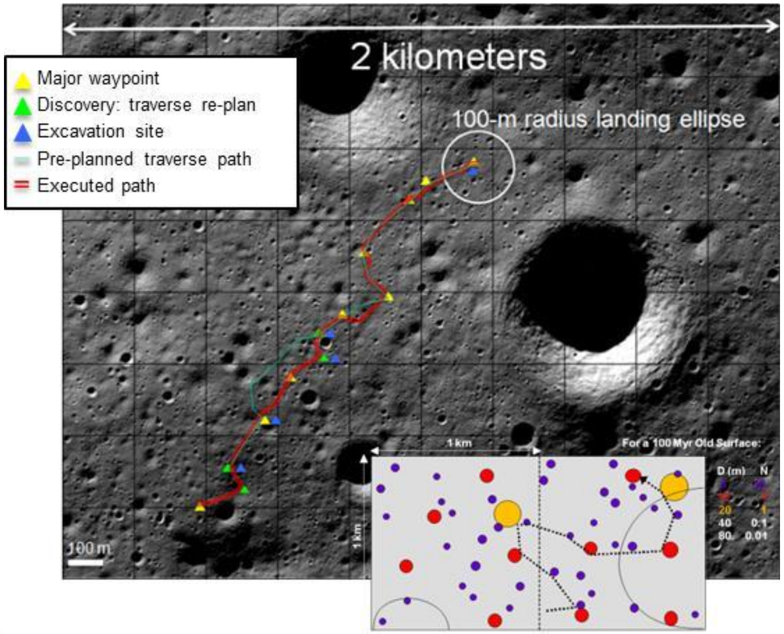
…but how are they distributed and accessed at the "human" level?

Determining ‘Operationally Useful’ Deposits

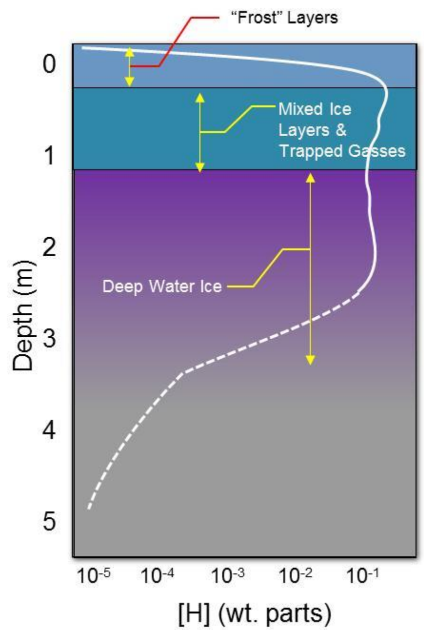
We know that water and other volatiles are there, but not known at the scales of utilization

Need to assess the extent of the resource ‘ore body’

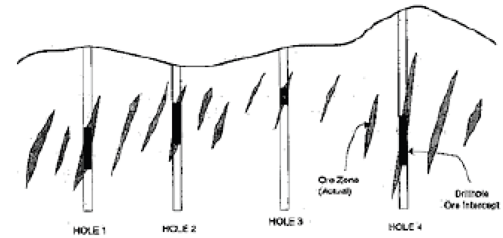
Local Regions (100s to 1000s of meters)



Vertical Profiles



Distribution and Form



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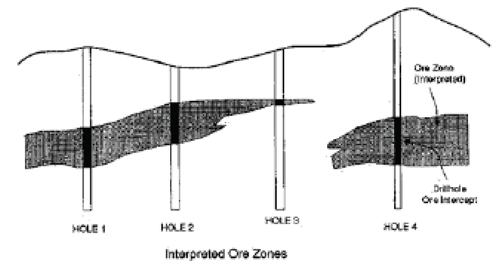


An ‘Operationally Useful’ Resource Depends on What, How much, and How often it is needed, and its Accessibility.

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**

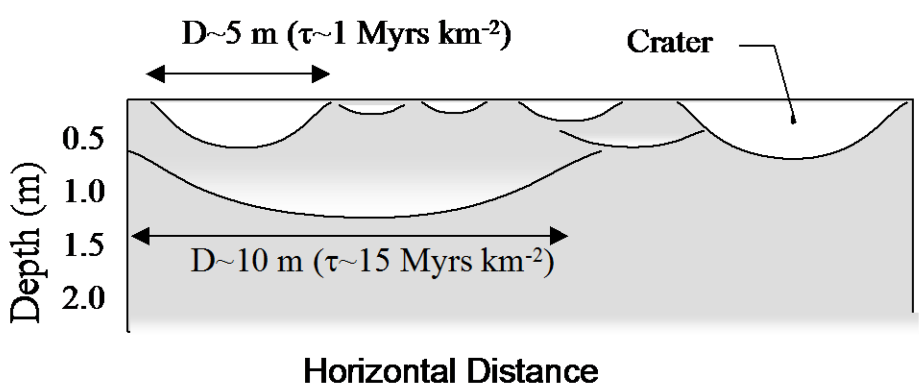
Resource Spatial Extent and Distribution

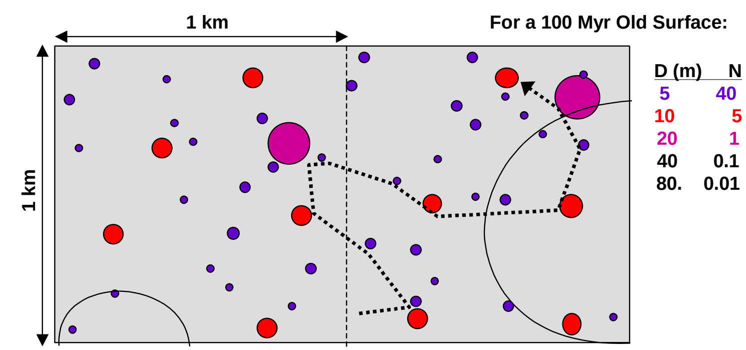
Spatial distribution

- Distribution of volatiles is likely governed by small impact cratering
- Distance between 10m wide craters (~1m deep) is ~50-150m
- Distance between 5m wide craters (~0.5m deep) is ~30-100 m

Consequently…

- Top 0.5 meters is likely to be patchy at scales of 10s-100s of meters
- “Mixing time scale” will increase with depth (less frequent larger impacts), thus horizontal spatial uniformity should increase with depth
- Implies that increased mobility reduces depth requirement for sampling
- Assuming 0.5% water ice between 0.5-1 m deep, 1 metric tonne of O_2 will require ~300 m^2 of regolith excavated to 1 m deep





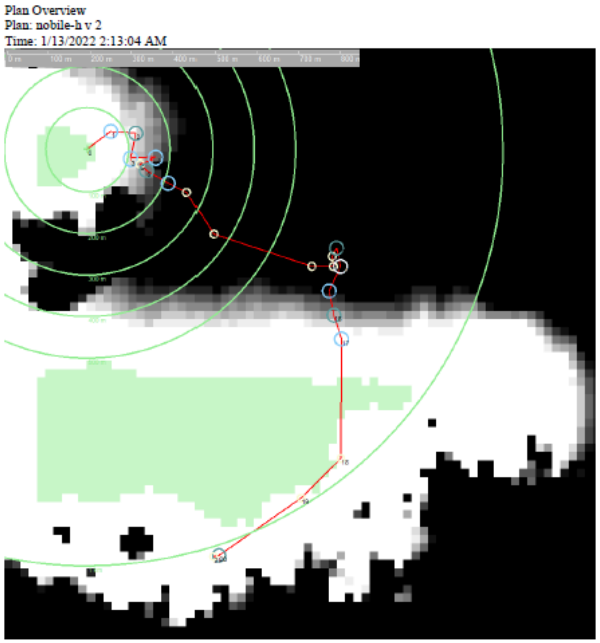
RP Traverse and Measurements

Prospecting:
- While roving, near continuous observations from a neutron spectrometer, provides bulk hydrogen down to 1m, and NIR spectrometer, providing surface hydration
- Identifies key areas for subsurface evaluation activities

Near Surface Assay (NSA)
- Drilling to a specified depth, up to 1-m; each 10-cm segments are exposed for examination by NIR spectrometer and high-res multi-color camera system
- Identifies volatile content with depth, constrains neutrons

Volatile Analysis (VA)
- Captures up to 15 grams of material from drill and warms to 150° C and 450° C
- Baked-0ff gasses analyzed by GC/MS
- Provides analytical determination of compound type (1-70AMU) and concentration

Nobile North Ridge Traverse Plan



Planned Traverse to Meet Mission Full Success
- Plans done for North Pole site Hermite-A and South Pole Nobile North Ridge
- Includes small-scale (8x8m in sun an 8x4m in shadow) Area of Interest Mapping (AIM)
- Full Success includes 10 “Science Stations” (SS), 3 in each environment type, except for PSRs which has 1 Station
- In each SS, AIM, 2 NSAs & 1 VA, except in PSR which has just a VA