National Aeronautics and Space Administration

Lunar Prospecting
The Why, What and How

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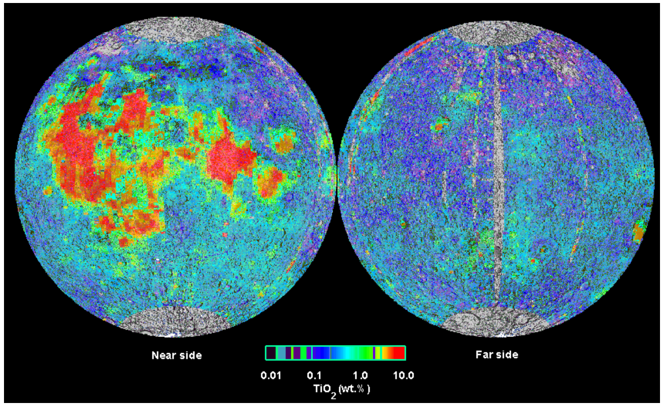
Understanding Lunar Resource Potential

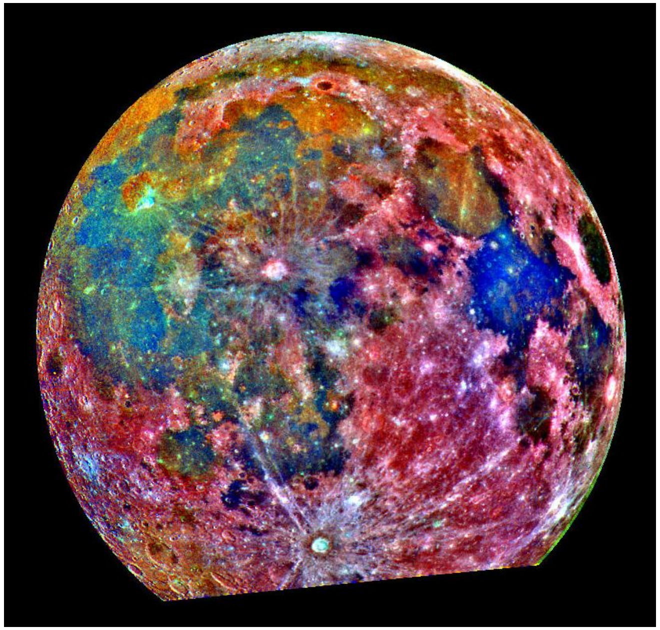
Already have a significant start to understanding the resource potential of the Moon

- Remote sensing has shown significant deposits of hydrogen and oxygen rich materials, in a variety of forms
- Several ISRU pathways have been developed over the last few decades, e.g., hydrogen reduction vs water extraction

Ultimately need to understand:

- The influence any one of these approaches has on future NASA architectures
- The economics of locating, extraction and processing
- Future remote surveys are still valuable, but are limited in resolution, sensing range, or complexities in interpretation





The LCROSS Experiment: Smooth or Chunky?

Evenly Distributed, low concentrations
"Smooth"

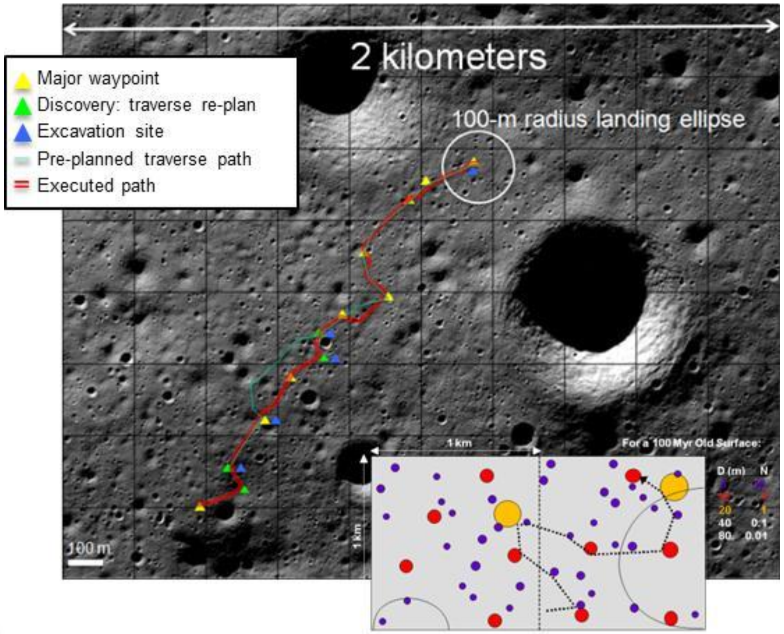
Higher, infrequent concentrations
"Chunky"

Processes such as impacts, diffusion, topography and sputtering may effect the distribution at a variety of scales

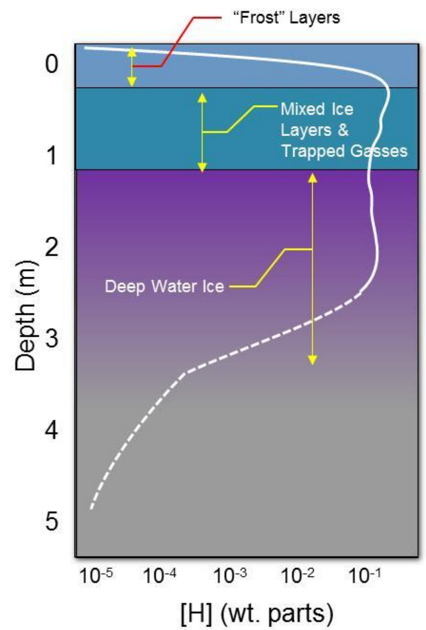
Determining ‘Operationally Useful’ Deposits

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

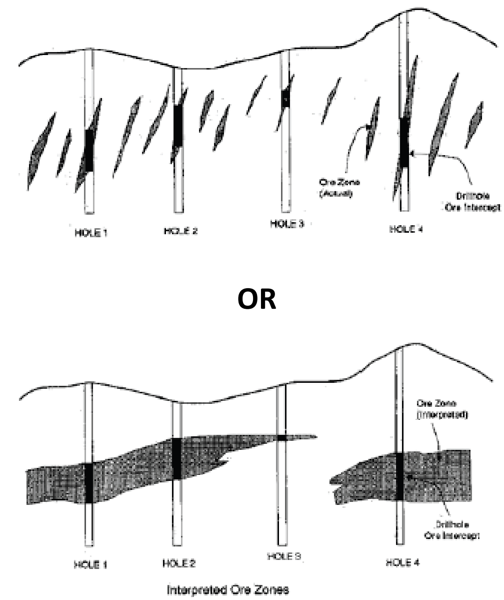
Need to Evaluate Local Region (1 to 3 km)



Need to Determine Vertical Profile



Need to Determine Distribution



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

Need to determine the potential (concentrations, forms, and accessibility) at the “human scale”

- 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

A little RP History

- The RESOLVE ISRU payload has been under development since before 2005, with several field tests completed by 2010

- Early lunar polar mission studies, e.g., RLEP-2, had very similar goals, but a a larger scale

- M3 and LCROSS findings catalyzed an architecture design effort which looked at possible prospecting / ISRU-demonstration missions

RESOLVE “Sun & Shadow” DRM 2.2

October 18, 2011

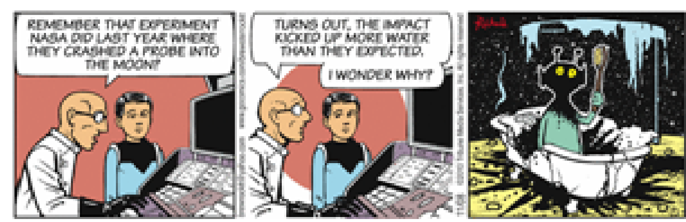
RESOLVE Architecture Team

JSC: Jeff George, Greg Mattes, Katie Rogers, Darby Magruder, Aaron Paz, Helen Vaccaro, et.al.

KSC: Jim Smith, et.al.

ARC: Tony Colaprete, Rick Elphic, et.al.

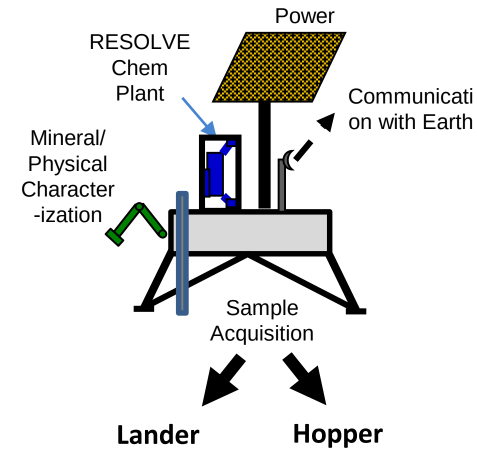
GSFC: Therese Suaris



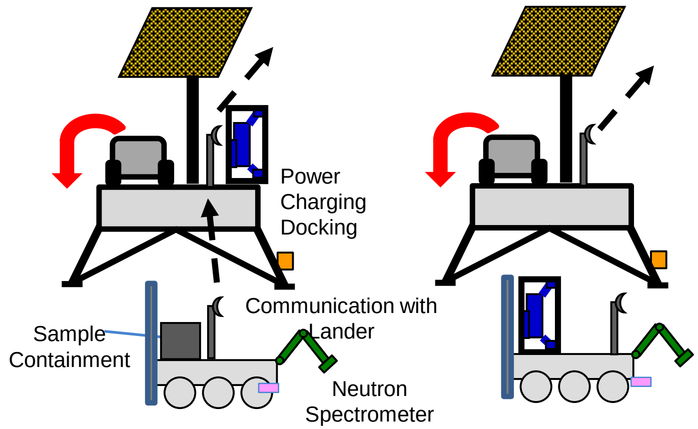
RESOLVE Mission Options

Mission Architecture Qualitative Comparison of Scenarios

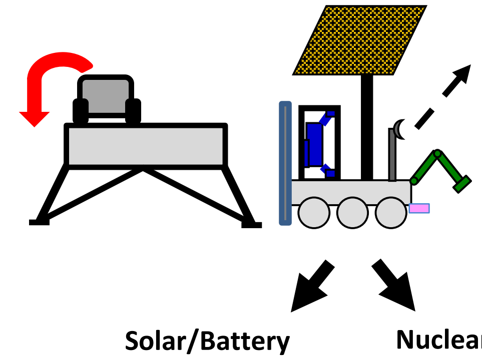
All on Lander



Split Capabilities Between Lander and Rover



All on Rover



		MISSION SCENARIO:					
		Land & Die	Hopper	Crawl & Die	Sun-Loving Rover	Sun & Shadow Rover	Radioisotope Rover
FIGURE OF MERIT	LOCATION	PSR	PSR, Regional	PSR	Sunlit	Sunlit w/ brief shadow	PSR, Regional
	SCIENCE RETURN	PSR 1 Bore, No Horiz. Surveys	Regional Exploration	PSR	Sunlit	Sunlit w/ brief shadow	Regional Exploration Extended Mission
	COST	1 DDT&E	1 DDT&E, Large ELV	2 DDT&E	2 DDT&E	2 DDT&E	2 DDT&E, Nuclear Extended Ops
	RISK	Low Tech, Low Prog, High Sci.	Med Tech	Med Tech (cold)	Low Tech, Low Prog, Med Sci.	Low All	High Prog. High Cost
Comments:		Cheapest groundtruth	Extra science possible over lander	Short duration but reasonable science	Limited science but low risk	Good Balance	Great science return but expensive

“Sun & Shadow” Rover Selected as Point-of-Departure for next Analysis Phase

Resource Prospector – Expedition 1

The Resource Prospector Design evolved out of the RESOLVE DRM

- Payload is based on the RESOLVE payload
- 300 kg-class rover mobility
- 1 meter Subsurface access
- Solar powered, with dips into shadow
- Class D / Cat III

Unique CONOPS

- Based on low-latency communications, but not tele-operated
- Real-time Science Decision making with direct input to rover driver and payload operations

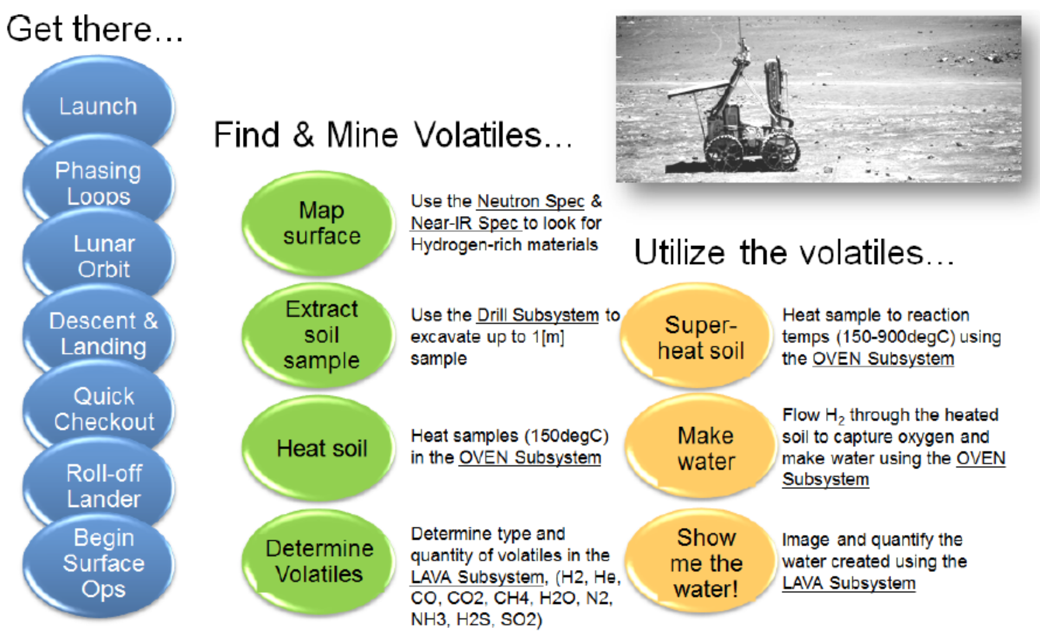


Figure: Simplified View of Resource Prospector Mission (RP)

The DRM is a balance between Project Scope and Addressing SKGs

SKGs Addressed by RP

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

The Mission "Plan"

To meet Full Mission Success:

- *Prospect:* Real-time for hydrogen rich materials while roving
- *Sampling:* Extraction of materials from as deep as meter for evaluation and processing
- *Processing* of samples captures in sunlit and shadowed regions

General CONOPS

- Mission is not tele-operated (telemetry latency is too high for "joy-sticking"; will use a combination of near real-time hazard assessment and way-point automated driving
- Areas of Interest identified pre-landing with traverses planned to these areas
- Once in an area a range of activities are planned for
- All the while keeping the rover in sun (unless shadowed ops are planned) and in comm (no operations planned during LOS)

*"In preparing for battle I have always found that **plans** are useless, but **planning** is indispensable." - Dwight D. Eisenhower*

Erlanger Traverse Exercise

Identified landing site and three areas of interest (AIs):

Landing site in area with persistent sun

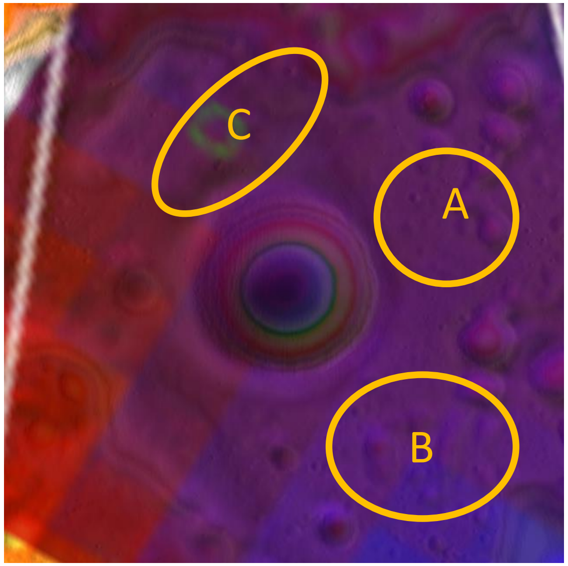
Area A: Toward increasing [H], low slopes, numerous smaller PSRs

Area B: Max [H] between Erlanger and Fibiger, coldest Max Temps, however, steeper slopes, and a long drive (~10 km) from notional landing sites

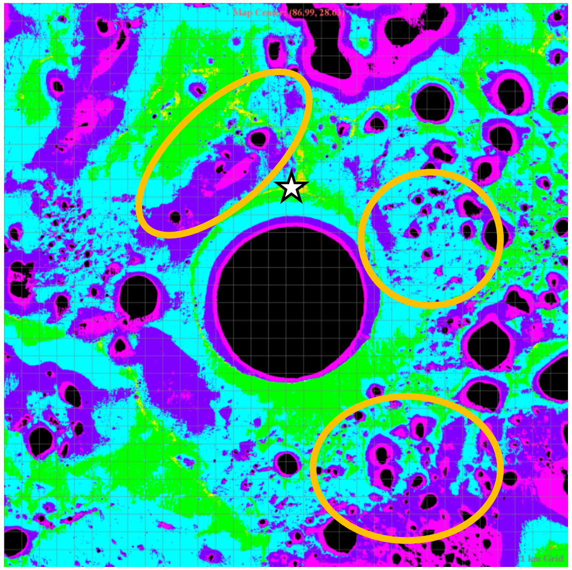
Area C: Valley poleward of Erlanger, toward Peary, with significant cold subsurface area

DTE is best to the south of Erlanger, so one strategy might be to start at the landing site and work clockwise around the crater, making timed sorties to Areas of Interest

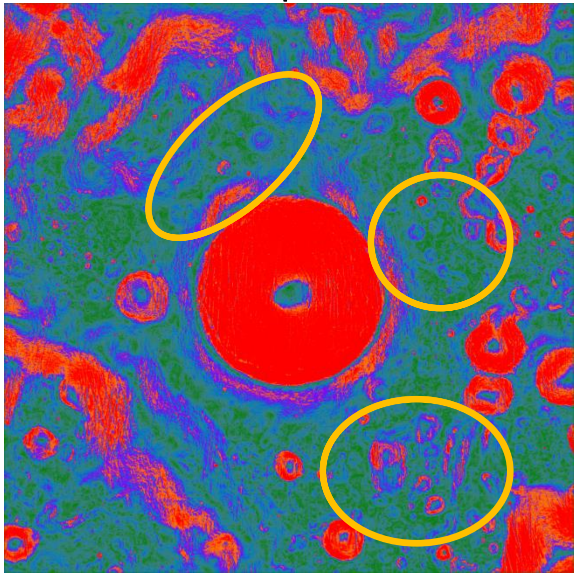
Hydrogen



% Sun

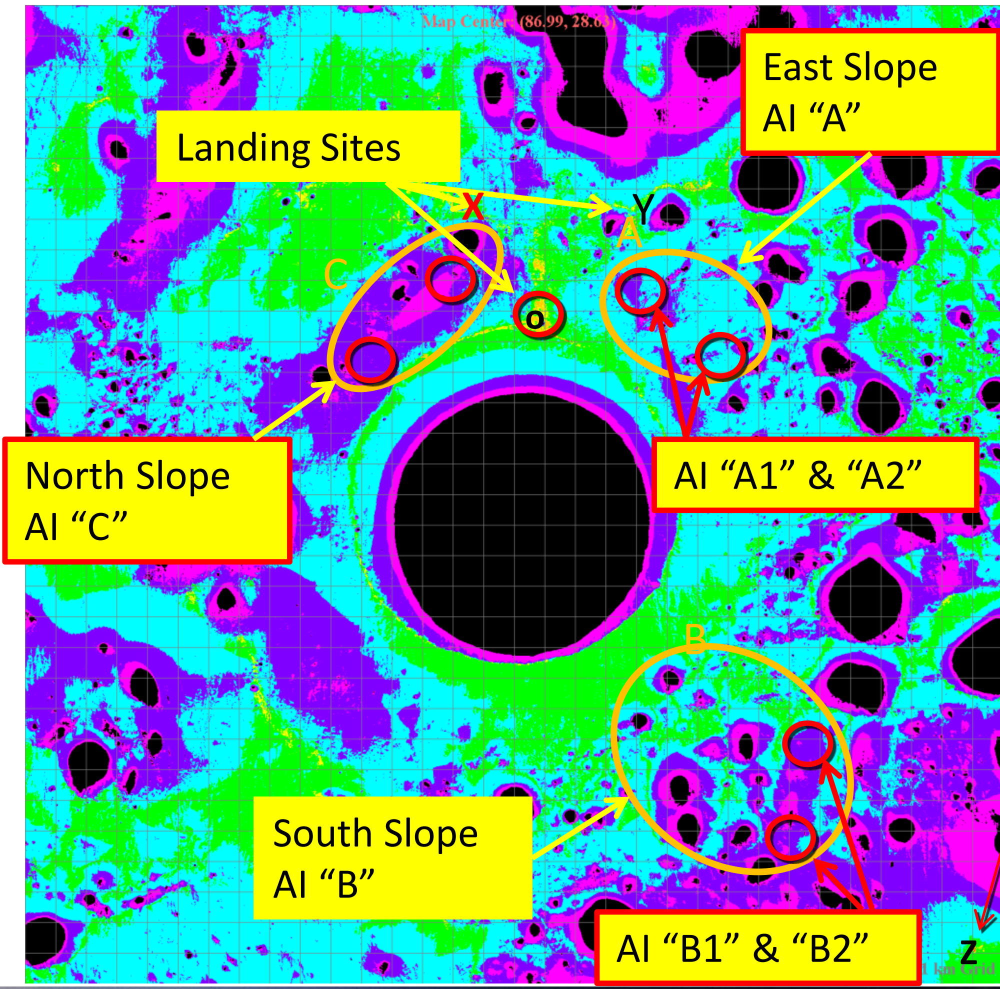


Slopes



Erlanger Rim Landing Site

- These landing sites generally allow of significant solar illumination
- Consider as starting points for traverse



Landing Sites:

87.1820°N, 29.0166° E (see "**o**")

AI "C" Alt: 87.2984° N, 27.5640° E (see "**X**")

AI "A" Alt: 87.3151° N, 32.9258° E (see "**Y**")

AI "D" Fibiger rim landing site: 86.4664° N, 36.7120° E (see "**Z**")

Areas of Interest Sub-Sites:

A1: 87.2188° N, 30.9253° E

A2: 87.1415° S, 33.1554° E

B1: 86.7308° N, 34.3039° E

B2: 86.6112° N, 33.7669° E

C1: 87.1312° N, 25.3443° E

C2: 87.2038°N, 28.7897° E

Start from Landing Sitex nearest AIs

- Land at "o" or "Y" to traverse AI Sub-Sites "A1" then to "A2" or "X" to traverse to AI "C"
- Land at "Z" (Fibiger) to traverse to AI Sub-Sites "B1" then to "B2"
- Assume first sub-site has priority, but can give up either sub-site within a single large AI to achieve a site in a second large AI (e.g., skip "A1" to get "A2" to insure we get "B1")

Issues Working In Lunar Polar Environment

Power and Comm:

- Low sun and Earth (for DTE) angles
- Multi-path comm losses
- Potential charging in shadows (lack of grounding plasma)
- Line-of-site limitations for comm relay

Roving:

- Traversing in soft soil
- Slippage or Burial and Active vs inactive suspension
- Sharp thermal gradients across rover and variable thermal interface with surface

Drilling:

- Understand rover/drill interactions on under lunar loading and slopes
- Slip/unintended motion
- Unknown near-surface regolith compaction profile / pre-load requirements

Navigation:

- Performance of stereo vision for hazard detection and localization
- Performance of active illumination (flood lighting and laser projection)
- Positive and negative obstacles (size, shape, distribution, composition)
- Regolith/rock optical properties (reflectance, opposition surge, etc)

RP – Expedition 1 is Just One Next Step

RP – *Expedition 1* will provide critical data necessary to evaluate the overall resource potential of the Moon

RP Will Provide Critical Feed-forward Data:

- **Ground truth on lunar polar soil and regolith mechanics, in sunlight and shadow, both at the surface and to depths of 1 meter**
  - *Provides critical engineering data for future landed missions (will address, in some fashion, points on previous slide)*
  - *Helps to interpret remote observations*
- **Measure of hydrogen bearing materials at scales currently not measurable remotely (e.g., neutron rates at scales of meters to kilometers) across a range of surface and subsurface environments**
  - *Provides first "human scale" assessment of resource potential; Is there significant variability at small scales across the range of environments*
  - *Demonstrates a range of tools, from hardware to operations, unique to lunar polar missions*

Candidate Next Steps after RP – E1

Higher resolution remote sensing of hydrogen/ices

- A map of hydrogen, for example, at 5-7km resolution would be searchable by RP
- Lunar Flashlight and LunarH-Map are good examples of on-the-books missions; several other candidates (e.g., See Spudis, LEAG 2015)

Improved surface data products

- Currently the lunar DTMs are good only to ~5 meters (where good stereo is available)
- Laser altimeter DTMs (e.g., LOLA) have significant gaps between orbit tracks; Registration offsets between data sets still exist
- For traverse planning (pre- and post landing) surface data products at ~1 meter scale are desired (impacts the speed made good once on the surface); Hazard assessments at scales <2 meters down to <10cm

ASRG power augmentation

- May significantly increase prospecting rate/range and duration in shadows
- May allow for lunar night survival

Deep PSR Access (e.g., Cabeus)

- Static lander might be fine, unless there is significant lateral heterogeneity
- Deeper subsurface sampling may offset lateral heterogeneity

Extended Communications

- DTE via relay from rover to lander looked limiting, unless lander was on a high point above prospecting "fields"
- Establishing strategically placed comm relays would facilitate much broader and unconstrained operations

Only when data from RP is synthesized with existing data and new remote data will the appropriate next steps be more obvious.