National Aeronautics and Space Administration

Future Missions & In Situ Resource Utilization (ISRU) Requirements

Presentation to Keck Study Workshop

"New Approaches to Lunar Ice Detection and Mapping"

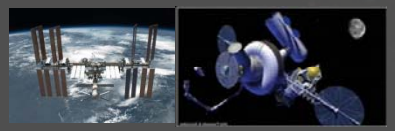
July 22,, 2013

Gerald (Jerry) Sanders
NASA/JSC
gerald.b.sanders@nasa.gov

Stepping Stone Approach for Demonstration & Utilization of Space Resources

Microgravity Processing & Mining

ISS & Space Habitats



ISRU Focus
- Trash Processing into propellants
- Micro-g processing evaluation
- In-situ fabrication

Purpose: Support subsequent robotic and human missions beyond Cis-Lunar Space

Near Earth Asteroids & Extinct Comets

ISRU Focus
- Micro-g excavation & transfer
- Water/ice prospecting & extraction
- Oxygen and metal extraction
- In-situ fabrication & repair
- Trash Processing

Phobos

ISRU Focus
- Micro-g excavation & transfer
- Water/ice and volatile prospecting & extraction

Purpose: Prepare for orbital depot around Mars

Purpose: Prepare for Phobos & future Space Mining of Resources for Earth

Planetary Surface Processing & Mining

Moon

ISRU Focus
- Regolith excavation & transfer
- Water/ice prospecting & extraction
- Oxygen and metal extraction
- Civil engineering and site construction

Purpose: Prepare for Mars and support Space Commercialization of Cis-Lunar Space

Mars

ISRU Focus
- Mars soil excavation & transfer
- Water prospecting & extraction
- Oxygen and fuel production for propulsion, fuel cell power, and life support backup
- Manufacturing & Repair

Purpose: Prepare for human Mars missions

What is Required to Utilize Space Resources?

- **Understand the resources**
  - What resources are there (minerals, volatiles, water/ice)?
  - How abundant is each resource?
  - What are the areal and vertical distributions and hetero/homogeneity?
  - How much energy is required to locate, acquire and evolve/separate the resources?

- **Understand environment impact on extraction and processing hardware**
  - What is the local temperature, illumination, radiation environment?
  - What are the physical/mineralogical properties of the local regolith?
  - Are there extant volatiles that are detrimental to processing hardware or humans?
  - What is the impact of significant mechanical activities on the environment?

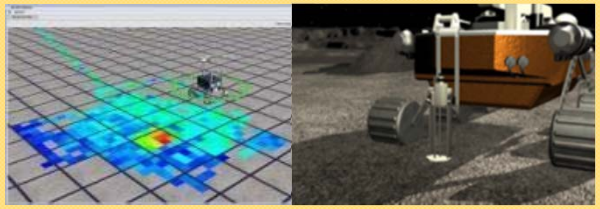
- **Design and utilize hardware to the maximum extent practical that has applicability to follow-on ISRU missions to utilize lunar volatiles (and other locations)**
  - Can we effectively excavate and transfer material for processing?
  - Can we effectively separate and capture volatiles of interest?
  - Can we execute repeated processing cycles (reusable chamber seals, tolerance to thermal cycles)?
  - Can we operate in shadowed areas for extended periods of time?

Space 'Mining' Cycle: *Prospect to Product*

Resource Assessment (Prospecting)

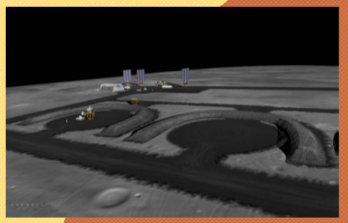
Global Resource Identification

Local Resource Exploration/Planning



Mining

Communication & Autonomy



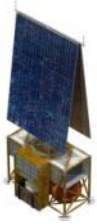
Maintenance & Repair

Site Preparation & Infrastructure Emplacement

Crushing/Sizing/ Beneficiation

Processing

Power



Propulsion

Life Support & EVA

Depots

Product Storage & Utilization

Waste

Remediation

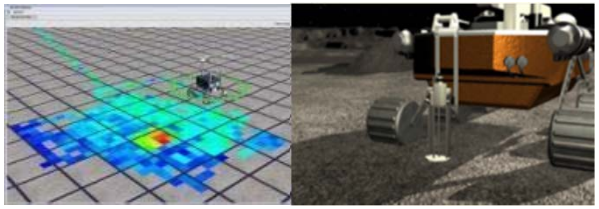
Spent Material Removal

Space 'Mining' Cycle: *Prospect*

Resource Assessment (Prospecting)

Global Resource Identification

Local Resource Exploration/Planning



Possible Lunar ISRU Robotic Mission Sequence

Polar Resource/ISRU Proof-of-Concept Demo(s)

Purpose: Scout

- Understand and characterize the resources and environment at the lunar poles for science and ISRU
- Determine the 'economic' feasibility of lunar polar ice/volatile mining for subsequent use

Oxygen Extraction from Regolith/Solar Wind Volatiles

Critical Function Demo

Polar Ice/Volatile Extraction

Purpose: Demo

- Verify critical processes & steps
- Verify critical engineering design factors for scale-up
- Address unknowns and Earth based testing limitations
- Characterize local material/resources
- Identify life issues

Pilot-Scale Operations

Purpose: Utilize

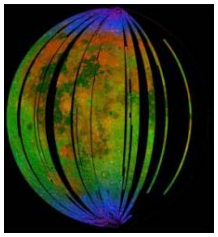
- Enhance or extend capabilities/reduce mission risk
- Verify production rate, reliability, and long-term operations
- Verify integration with other surface assets
- Verity use of ISRU products for full implementation

Which path depends on results of proof of concept mission(s)

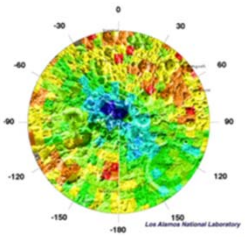
Global Assessment of Lunar Volatiles

Apollo Samples

Moon Mineralogical Mapper (M^3)

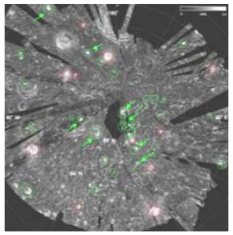


Lunar Prospector
Lunar Recon Orbiter (LRO)



Lunar Crater Observation & Sensing Sat. (LCROSS)

Clementine
Chandrayaan
LRO
Mini SAR/RF



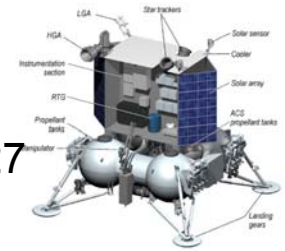
	Solar Wind	Core Derived Water	Water/Hydroxyl	Polar Volatiles	Polar Ice
Instrument	Apollo samples Neutron Spectrometer	Apollo samples	M3/LRO	LCROSS	Mini SAR/RF
Concentration	Hydrogen (50 to 150 ppm) Carbon (100 to 150 ppm) Helium (3 to 50 ppm)	0.1 to 0.3 wt % water in Apatite 0 to 50 ppm water in volcanic glass	0.1 to 1% water; 1-2% frost 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

Type and Scale of Prospecting Needed to Utilize Lunar Volatiles

Exploratory Assessment

- Short duration mission:
  - 5 to 9 days
  - Hours in shadowed area
- Validate design and operation of hardware
- Evaluate physical and mineral properties of polar regolith
- Evaluate distribution of polar volatiles in 1 to 3 km area
  - Neutron & Near IR spectrometer
  - 3 to 5 cores; 1 to 2 meters deep
  - GC, MS & IR volatile measurements
- Validate site selection approach for locating volatiles at lunar poles *(missions to different destinations? Data sharing-competitors?)*

Resource Prospector (RESOLVE)



Luna 25/27

Focused Assessment

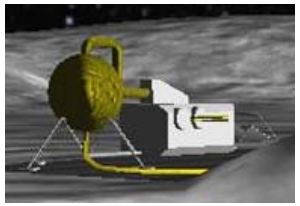
- Long duration mission:
  - 6+ months
- Perform more extensive evaluation of volatile distribution in polar region: larger area and more samples
- Demonstrate extended operations in polar shadowed region
- Examine contaminants in water collected
- Validate site selected for long-term mining operations
- *Map the location & concentration of the lunar volatile resources*

Economic Feasibility Assessment

RLEP-2 Type Mission

Mining Feasibility

- Demonstrate ISRU hardware for sustained excavation, processing, collection and storage of polar water and other volatiles of interest present
- Demonstrate water cleaning, and processing
- Demonstrate fuel production (from carbon-bearing volatiles)
- Demonstrate long-term storage of products (O_2, CH_4)
- Demonstrate power system for extended duration operations in polar shadowed region
- *Determine mining, transportation, infrastructure and logistics needs to sustain mining operations*



Resource Prospector Mission

Regolith & Environmental Science and Oxygen & Lunar Volatile Extraction (RESOLVE)

RPM is an internationally developed (NASA and CSA) mission/payload that that can perform two important missions for Science and Human Exploration of the Moon

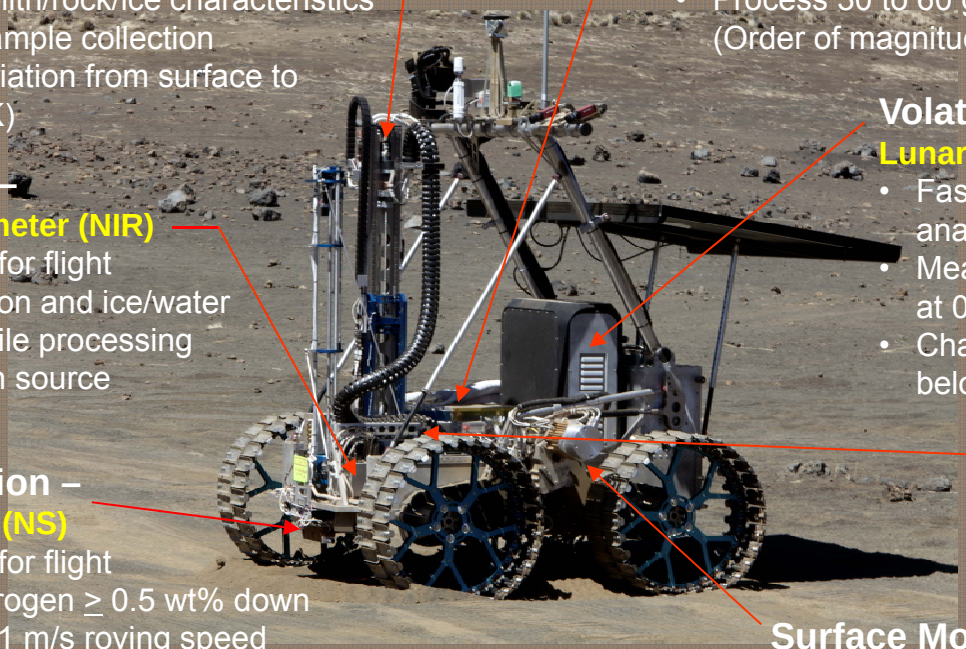
Prospecting Mission: (Polar site)

- ✓ **Verify the existence of and characterize the constituents and distribution of water and other volatiles in lunar polar surface materials**
  - **Map the surface distribution of hydrogen rich materials**
  - **Determine the mineral/chemical properties of polar regolith**
  - **Measure bulk properties & extract core sample from selected sites**
    - To a depth of 1m with minimal loss of volatiles
  - **Heat multiple samples from each core to drive off volatiles for analysis**
    - From <100K to 423 K (150° C)
    - From 0 up to 100 psia (reliably seal in aggressively abrasive lunar environment)
  - **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
    - Survive limited exposure to HF, HCl, and Hg

ISRU Processing Demonstration Mission: (Equatorial and/or Polar Site)

- ✓ **Demonstrate the Hydrogen Reduction process to extract oxygen from lunar regolith**
  - **Heat sample to reaction temperature**
    - From 150° C to 900° C
  - **Flow H_2 through regolith to extract oxygen in the form of water**
  - **Capture, quantify, and display the water generated**

Resource Prospector Mission



Sample Acquisition –
Auger/Core Drill [CSA provided]
- Complete core down to 1 m; Auger to 0.5 m
- Minimal/no volatile loss
- Low mass/power (<25 kg)
- Wide variation in regolith/rock/ice characteristics for penetration and sample collection
- Wide temperature variation from surface to depth (300K to <100K)

Sample Evaluation –
Near Infrared Spectrometer (NIR)
- Low mass/low power for flight
- Mineral characterization and ice/water detection before volatile processing
- Controlled illumination source

Resource Localization –
Neutron Spectrometer (NS)
- Low mass/low power for flight
- Water-equivalent hydrogen ≥ 0.5 wt% down to 1 meter depth at 0.1 m/s roving speed

Volatile Content/Oxygen Extraction –
Oxygen & Volatile Extraction Node (OVEN)
- Temperature range of <100K to 900K
- 50 operations nominal
- Fast operations for short duration missions
- Process 30 to 60 gm of sample per operation (Order of magnitude greater than TEGA & SAM)

Volatile Content Evaluation –
Lunar Advanced Volatile Analysis (LAVA)
- Fast analysis, complete GC-MS analysis in under 2 minutes
- Measure water content of regolith at 0.5% (weight) or greater
- Characterize volatiles of interest below 70 AMU

Operation Control –
Flight Avionics [CSA/NASA]
- Space-rated microprocessor

Surface Mobility/Operation [CSA mobility platform]
- Low mass/large payload capability
- Driving and situation awareness, stereo-cameras
- Autonomous navigation using stereo-cameras and sensors
- NASA contributions likely for communications and thermal management

RESOLVE Instrument Suite Specifications
- Nom. Mission Life = 10+ Cores, 12+ days
- Mass = 60-70 kg
- Dimensions = w/o rover: 68.5 x 112 x 1200 cm
- Ave. Power; 200 W

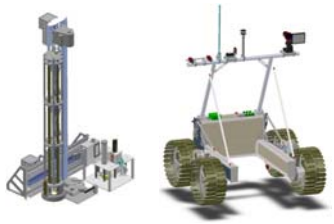
Lunar Resource Prospecting Instruments

Instrument Suite Recommended for RLEP-2	RESOLVE	Luna 27	Optimal Prospector
Lander Instruments			
Stereo Imaging System	360° camera capability	TV imaging	X
Beacon (navigation/data reference)		X	X
Langmuir probe (levitated dust)		Dust measurements	
Particle counter (levitated dust)			
Electron Paramagnetic Resonance Spectrometer (determine reactivity of dust for biologic implications)			
Sample Processing System		GC/MS and Laser MS	
Arm/Scoop		Possible arm/scoop	
		Drill (2 m)	
Geotechnical End Effectors			
		Mineral Eval: IR, UV, and optical imaging	
		Regolith thermal property measuremnt	
Magnets (for magnetic susceptibility)			
		Plasma/neutrals measurement	
		Sesimic activity measurement	
			Sesimic for subsurface features
Mobile Instruments			
Stereo Imaging System	Navigation and sample site imaging		X
Neutron Spectrometer	X		X
Ground Penetrating Radar			X
Drill (2 m)	X (1 m)		X
Arm/Scoop			
Geotechnical End Effectors	Measure while drilling		X
			Regolith thermal measurement
Magnets (for magnetic susceptibility)			
			Sesimic receiver
Sample Processing System	X		X
GC/MS	X		X
Tuneable Diode Laser	Mineral and H_2O/OH Eval: Near IR		Multiple mineral instruments and microscope

Possible Evolution of Surface Systems - Finding to Utilizing Polar Water/Volatiles

RPM Mission 1

Exploratory Assessment



RESOLVE 1.0 | Polar Rover 1.0

- Short Duration Mission
  - Short duration in shadowed area (hrs)
- Validate design and operation of hardware
- Evaluate distribution of polar volatiles in 1 to 3 km area
- Validate site selection approach for locating volatiles at lunar poles

RPM Mission 2

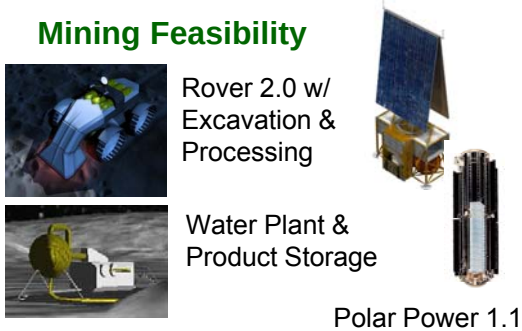
Focused Assessment

RESOLVE 1.1 | Polar Rover 1.1 | Polar Power 1.0

- Upgrade rover for longer term operation on the Moon and in shadowed areas
- Perform more extensive evaluation of volatile distribution in polar region: larger area/more samples
- Upgrade physical/mineral instruments
- Examine purity of water collected & possibly test cleaning technique
- Demonstrate power system for extended duration operations in polar shadowed region (*Note: mass estimate is based on remainder of lander payload capability*)

IceMiner Mission

Mining Feasibility



- Finalize polar rover design (tandem rover possible)
- Demonstrate ISRU hardware for sustained excavation, processing, and collection of polar water/volatiles
- Demonstrate water cleaning, processing, and storage
- Demonstrate fuel production (from carbon-bearing volatiles)
- Upgrade power system for polar operations
  - ➢ *Note: Size of stationary processing unit will be a function of lander payload and desired processing scale*

Notional Mission Evolution with ISRU

(for planning)

Resource Prospector Mission (RESOLVE)

Polar Volatiles &/or Oxygen from Regolith

Technology & ops

Technology & ops

Lunar Sample Return

Lunar Metal/Silicon Extraction

Mars Propellant Production

Mars ISRU Demo

Mars Sample Return w/ ISRU

In-Space Manufacturing

Asteroid Retrieval

NEA Resource Prospecting

NEA Resource Extraction

In-Space Propellant Depot

Human Cis-Lunar Missions

Human NEA Missions

Human Mars Missions

ISRU Development Areas vs Mission Applications

ISRU Development Areas	Resource Prospector (Moon, Mars, NEO)	Atmosphere Processing (Mars)	Regolith/Soil Processing for Water (Moon, Mars, NEO)	Material Processing for Oxygen/Metals (Moon, NEO)	Trash Processing to Fuel
Regolith-Soil Extraction					
Regolith (granular) Excavation & Transfer	X		X	X	
Hard Material Excavation & Transfer	P			P	P
Hydrated Soil /Material Excavation & Transfer	P		X	X	X
Icy-Soil Excavation & Transfer	X		X	X	
Resource Characterization					
Physical Property Evaluation	X				
Mineral/Chemical Evaluation	X			X	
Volatile-Product Analysis	X	X			X
Regolith-Soil Processing (Volatiles, O_2, Metal)					
Crushing			P	X	P
Size Sorting				P	
Beneficiation/Mineral Seperation				P	
Solid/Gas Processing Reactor	X		X	X	X
Solid/Liquid Processing Reactor				P	
Contaminant Removal			X	X	X

ISRU Development Areas	Resource Prospector (Moon, Mars, NEO)	Atmosphere Processing (Mars)	Regolith/Soil Processing for Water (Moon, Mars, NEO)	Material Processing for Oxygen/Metals (Moon, NEO)	Trash Processing to Fuel
Gas Processing					
Dust/Particle Filtration		X	X	X	X
CO_2 Capture - Separation		X		P	X
CO_2 Conversion into CO-O_2		P			
CO/CO_2 Conversion into H_2O-CH_4		P		P	X
H_2-CH_4 Separation		P		P	X
Water Processing					
Water Capture	X		X	X	X
Water Cleaup - Purity Measurment			X	X	X
Water Electrolysis		P	X	P	X
Regenerative Dryers		P	X	P	X
Support Systems					
Extended Operation Power Systems			P	P	
Extended Operation Thermal Systems			P	P	
Cryogenic Liquefaction, Storage, and Transfer					

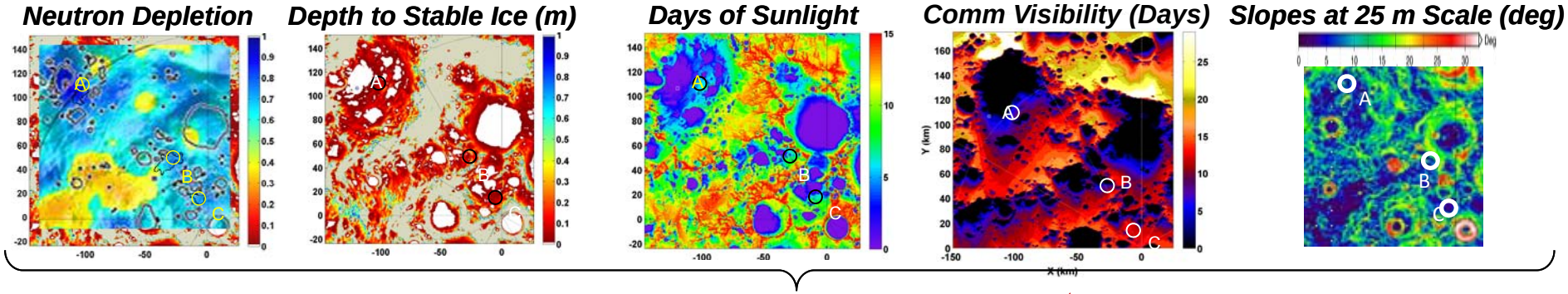
P = Possible need

Main Discriminators: material (physical, mineral) water content/form (ice, hydration, surface tension), gravity (micro, low), pressure, (vacuum, atm.), and weathering

Questions?

Backup

Lunar Volatile Site Selection - Prospecting Cycle



Select Site for Prospecting

Mining Feasibility results were not favorable

Exploratory Assessment results were not favorable

Perform Mining Feasibility

Perform Exploratory Assessment

Start Mining for Product

Mining Feasibility results were promising

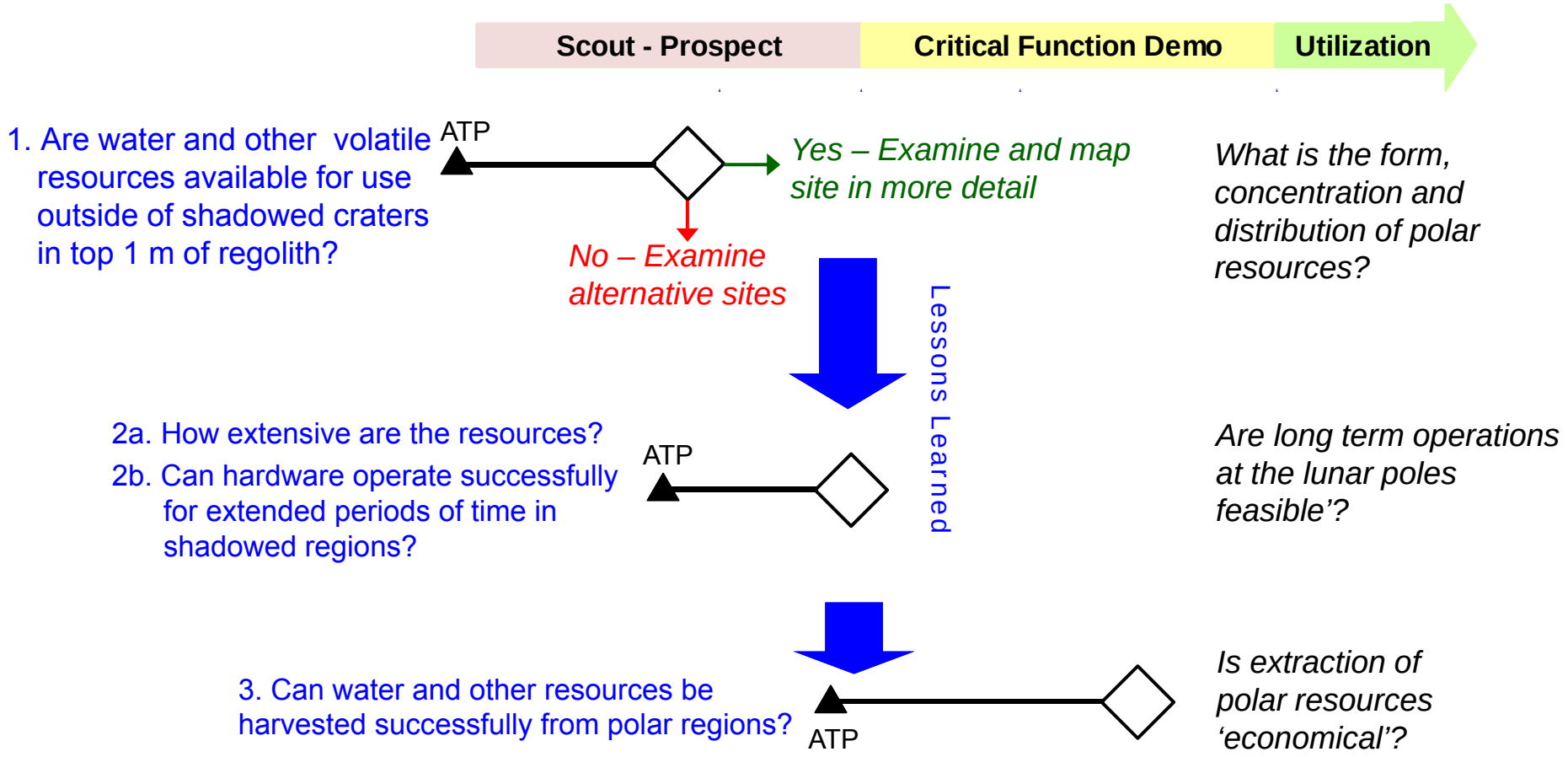
Focused Assessment results were not favorable

Exploratory Assessment results were promising

Focused Assessment results were promising

Perform Focused Assessment

Approach to Understanding Polar Volatile Resources and Retiring Risk is Required



ATP = Authority To Proceed

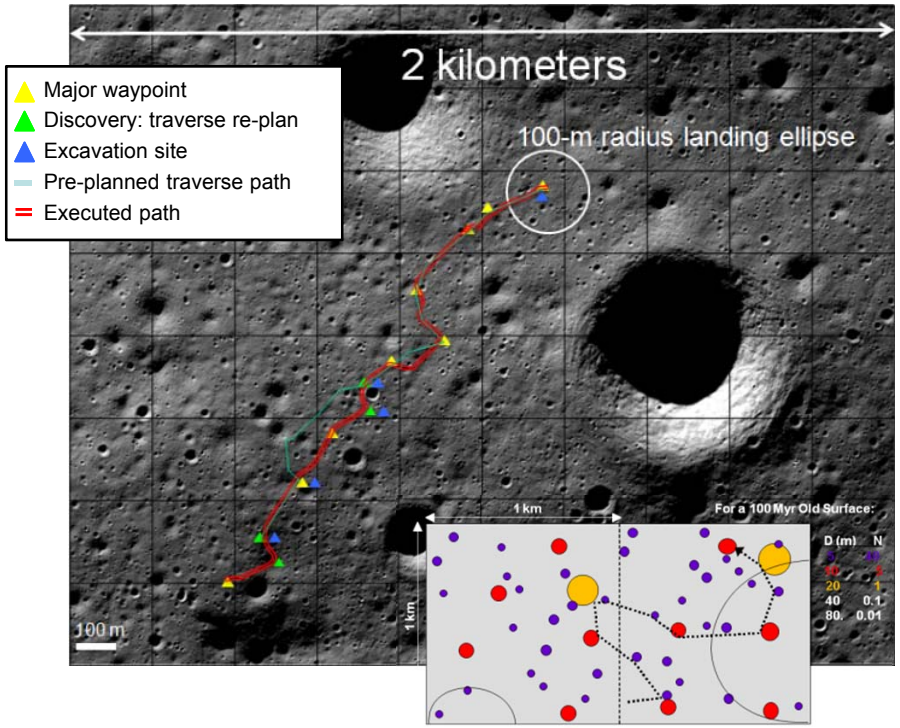
Key RESOLVE Mission Design Trades

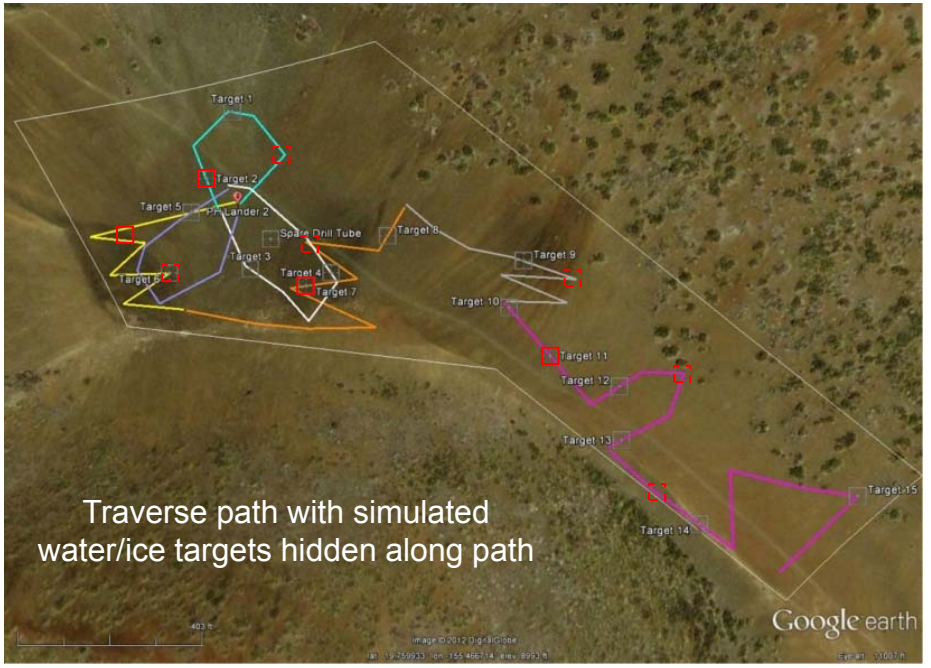
Mission Attributes	Base	Mid	Full
Location	Long duration sunlight	**Min. Sun/Shadowed**	Permanent Shadow
Sample Site Selection	Surface features/minerals	**Neutron Spec on Rover**	Neutron Spec with GPR
Subsurface Sample Acquisition	Arm/scoop	*Auger w sample transer*	**Core Drill/Push Tube w sample transfer**
Sample of Interest	Rock/regolith	Ice	**Polar volatiles**
Sample Depth	*<0.75 m*	**1.0 m**	2.0 m
Sample Measurement	Downhole Optical for ice	Oven w Tunable Diode Lasers	**Oven with GC/MS and Near IR**
Sample Preparation	**None**	Crushing	Thin Section
Mineral Characterization	None	**Single instrument - Near IR**	Multiple Instruments
Regolith/Dust Physical Characterization	None	**Camera & Drill Response**	Microscope & Geotechnical Instruments
Volatile/Product Collection	None	**Water**	Water and gas volatiles
Oxygen Extraction from Regolith	None	**H_2 Reduction w Same Oven**	Separate demo
Temperature/Radiative Environment Characterization	None	**External temp sensor**	Instrumented Radiator
Mobility	None - Lander	Hopper	**Rover**
Power	*Non-recharge battery*	**Battery/Solar Array**	Nuclear
Communications	**Direct to Earth-rover**	*Direct to Earth-lander; rover relay*	Comm Relay Satellite

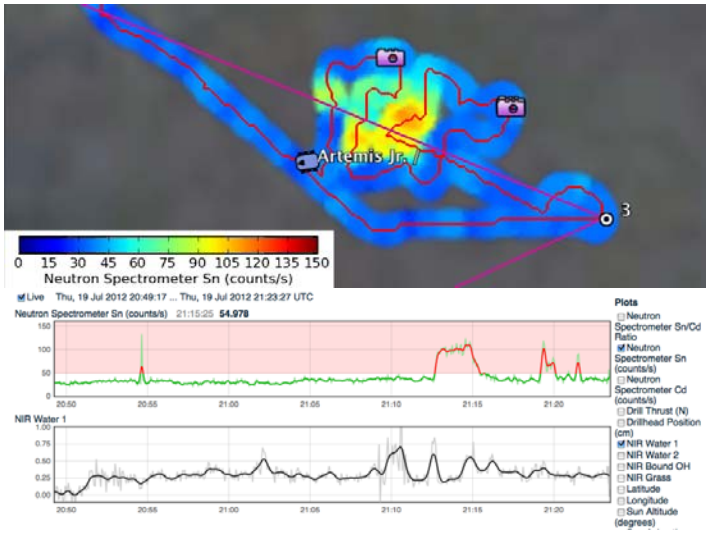
Blue Bold = Baseline

Red Italics = Backup

Exploratory Prospecting for Lunar Volatiles

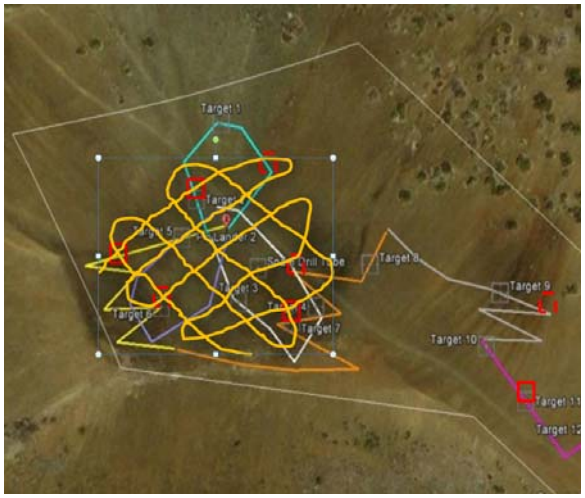






- Hypothesize location of volatiles based global data, terrain, and geological context
- Plan traverse before landing based on location estimates and rover capabilities
- Utilize non-invasive surface and subsurface instruments to guide selection of sample sites; Instrument suite may be limited
- Perform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

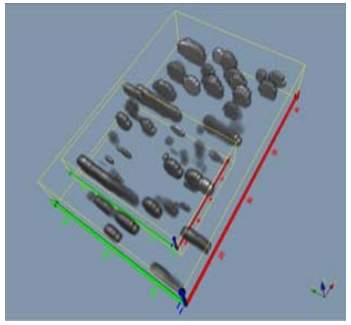
Focused Resource Assessment of Polar Volatiles

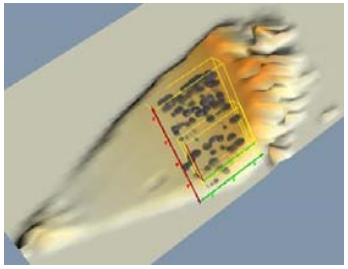


Traverse paths to fill in missing data

Rover-Data localization equipment

Rovers performing coordinated area assessment



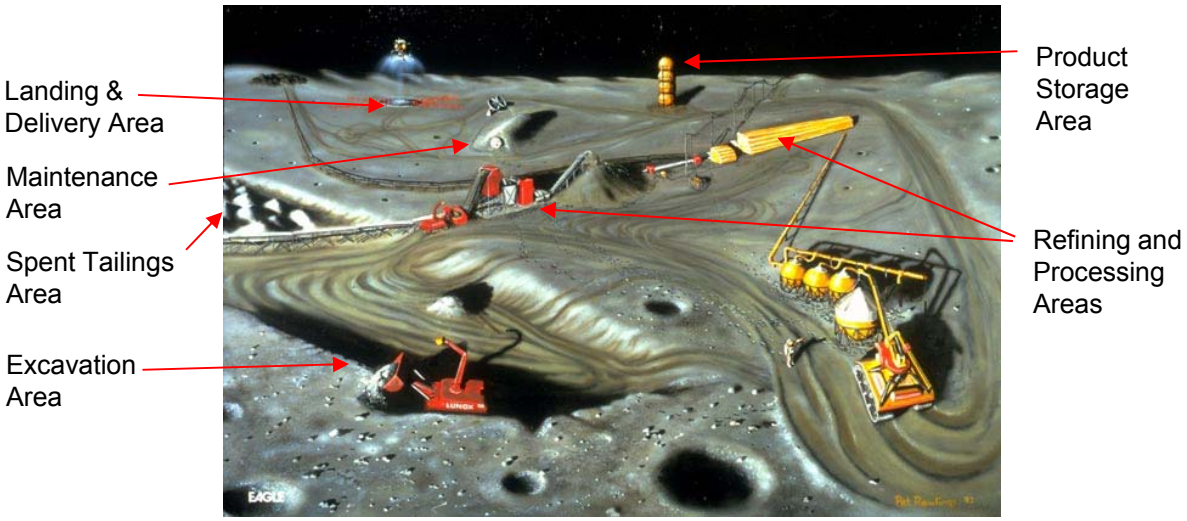


Data fusion with terrain information

- 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

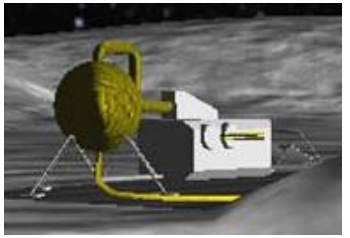
Mining Feasibility for Polar Volatiles

- 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.



Plan for Mine/Infrastructure Layout & Operation

Polar Mobility, Excavation & Processing



Water Plant & Product Storage

Polar Power System