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”

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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

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

Phobos

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

Purpose: Prepare for orbital depot around Mars

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

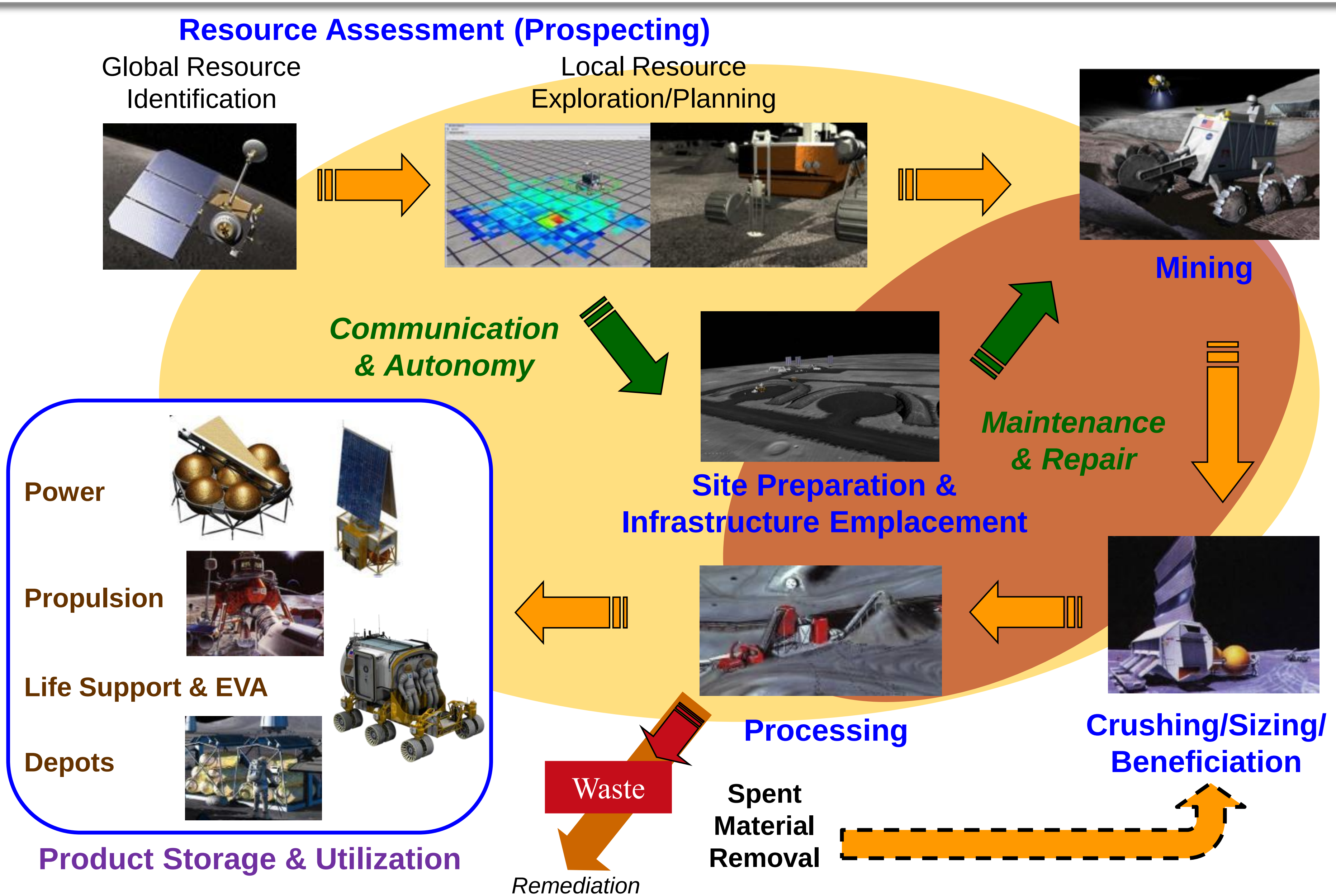
What is Required to Utilize Space Resources?

- **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 resources/volatiles (and other locations)**
  - Can we effectively excavate and transfer material for processing?
  - Can we effectively separate and capture resources/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*

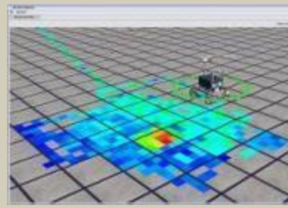


Space 'Mining' Cycle: *Prospect*

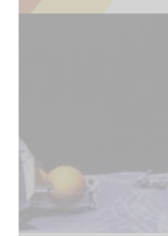
Resource Assessment (Prospecting)

Global Resource Identification

Local Resource Exploration/Planning



Mining

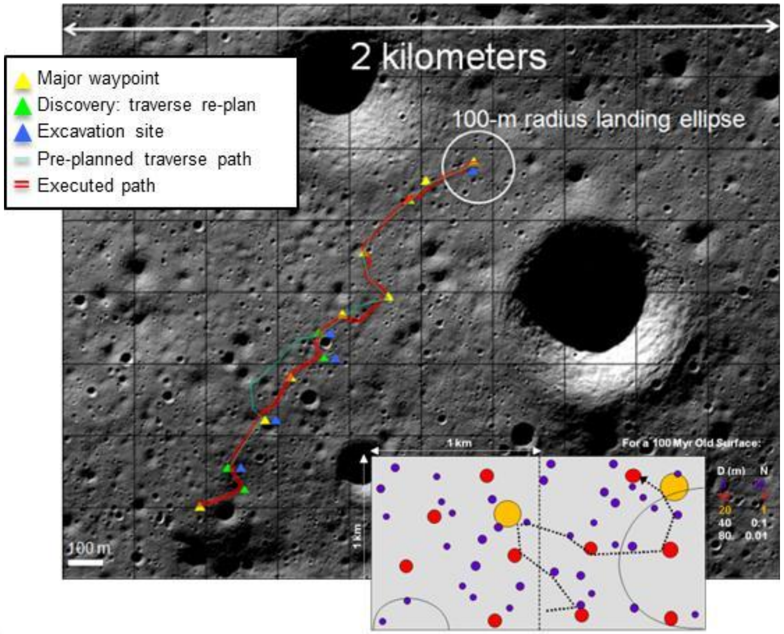


g/Sizing/ ciation

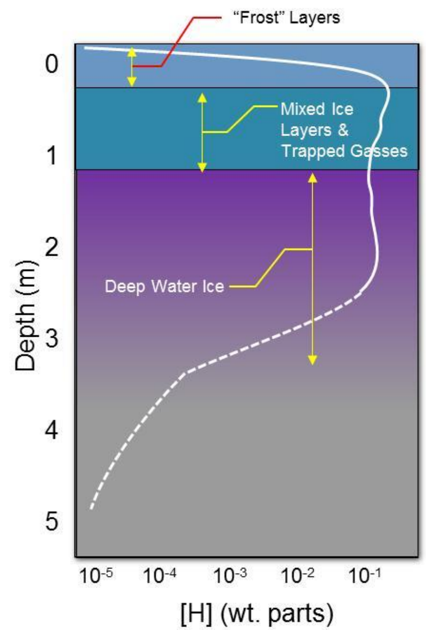
Determining 'Operationally Useful' Resource Deposits

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

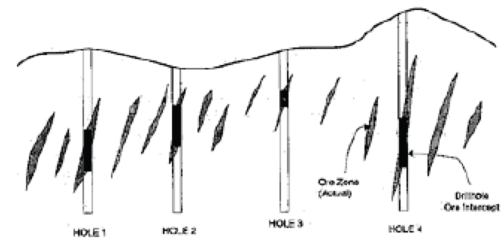
Need to Evaluate Local Region (1 to 3 km)



Need to Determine Vertical Profile



Need to Determine Distribution



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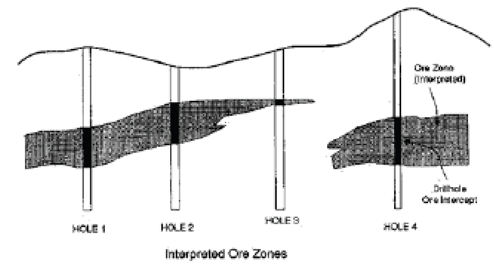


An 'Operationally Useful' Resource Depends on What is needed, How much is needed, and How often it is needed

Potential Lunar Resource Needs*

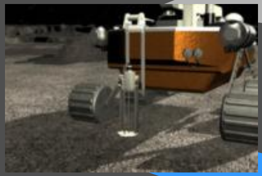
- 1,000 kg oxygen (O_2) per year for life support backup (crew of 4)
- 3,000 kg of O_2 per lunar ascent module launch from surface to L_1/L_2
- 16,000 kg of O_2 per reusable lunar lander ascent/descent vehicle to L_1/L_2 (fuel from Earth)
- 30,000 kg of O_2/Hydrogen (H_2) per reusable lunar lander to 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

Possible Lunar ISRU Robotic Mission Sequence

Oxygen Extraction from Regolith/Solar Wind Volatiles

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



Critical Function Demo

Pilot-Scale Operations

Polar Ice/Volatile Extraction

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

Purpose: Demo

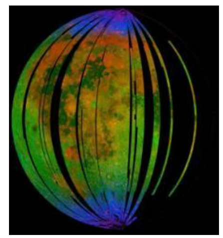
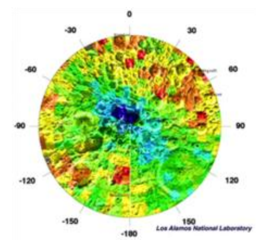
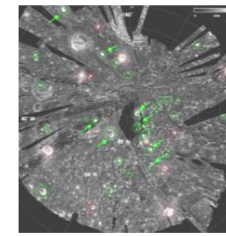
- Verify critical processes & steps
- Verify critical engineering design factors for scale-up
- Address unknowns and Earth based testing limitations
- Characterize local material/resources
- Identify life issues

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 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

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 or competitors?

Focused Assessment

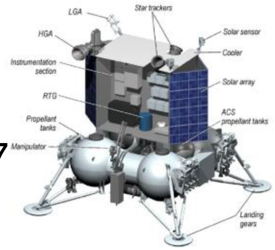
- Long duration mission:
  - 6+ months
- Perform more extensive evaluation of volatile distribution in polar region: larger area and more samples
- Demonstrate extended operations in polar shadowed region
- Examine contaminants in water collected
- Validate site selected for long-term mining operations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

Mining Feasibility

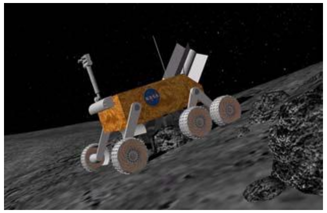
- Demonstrate ISRU hardware for sustained excavation, processing, collection and storage of polar water and other volatiles of interest present
- Demonstrate water cleaning, and processing
- Demonstrate fuel production (from carbon-bearing volatiles)
- Demonstrate long-term storage of products (O_2,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

Economic Feasibility Assessment

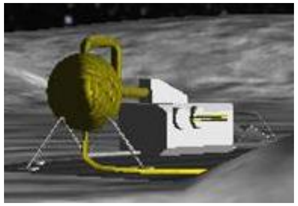
Resource Prospector (RESOLVE)



Luna 25/27



RLEP-2 Type Mission



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**

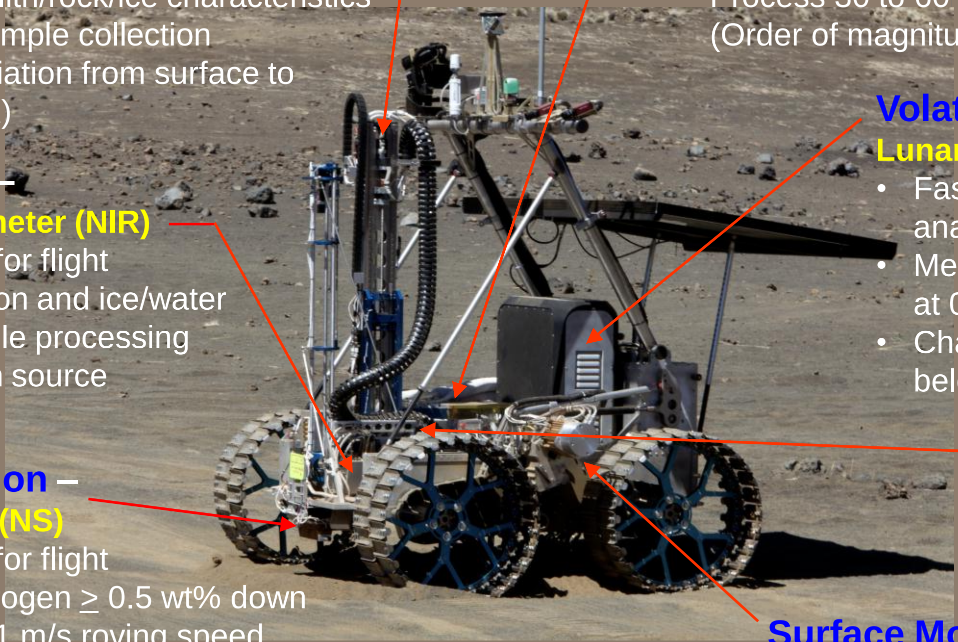
- **Map the surface distribution of hydrogen rich materials**
- **Determine the mineral/chemical properties of polar regolith**
- **Measure bulk properties & extract core sample from selected sites**
  - To a depth of 1m with minimal loss of volatiles
- **Heat multiple samples from each core to drive 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 $\geq$ 0.5 wt% down to 1 meter depth at 0.1 m/s roving speed

RESOLVE Instrument Suite Specifications
- Nom. Mission Life = 4+ cores, 5-7 days
- Mass = 80-100 kg
- Dimensions = w/o rover: 68.5 x 112 x 1200 cm
- Ave. Power; 200 W

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

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

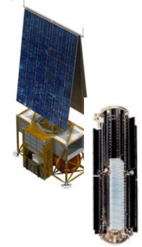
- Short Duration Mission
  - Short duration in shadowed area (hrs)
- Validate design and operation of hardware
- Evaluate distribution of polar volatiles in 1 to 3 km area
- Validate site selection approach for locating volatiles at lunar poles

RPM Mission 2

Focused Assessment

RESOLVE 1.1

Polar Rover 1.1



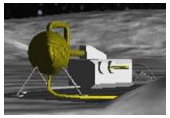
Polar Power 1.0

- 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*)

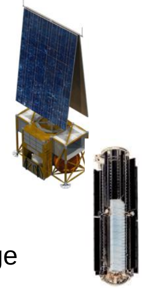
IceMiner Mission

Mining Feasibility

Rover 2.0 w/ Excavation & Processing



Water Plant & Product Storage

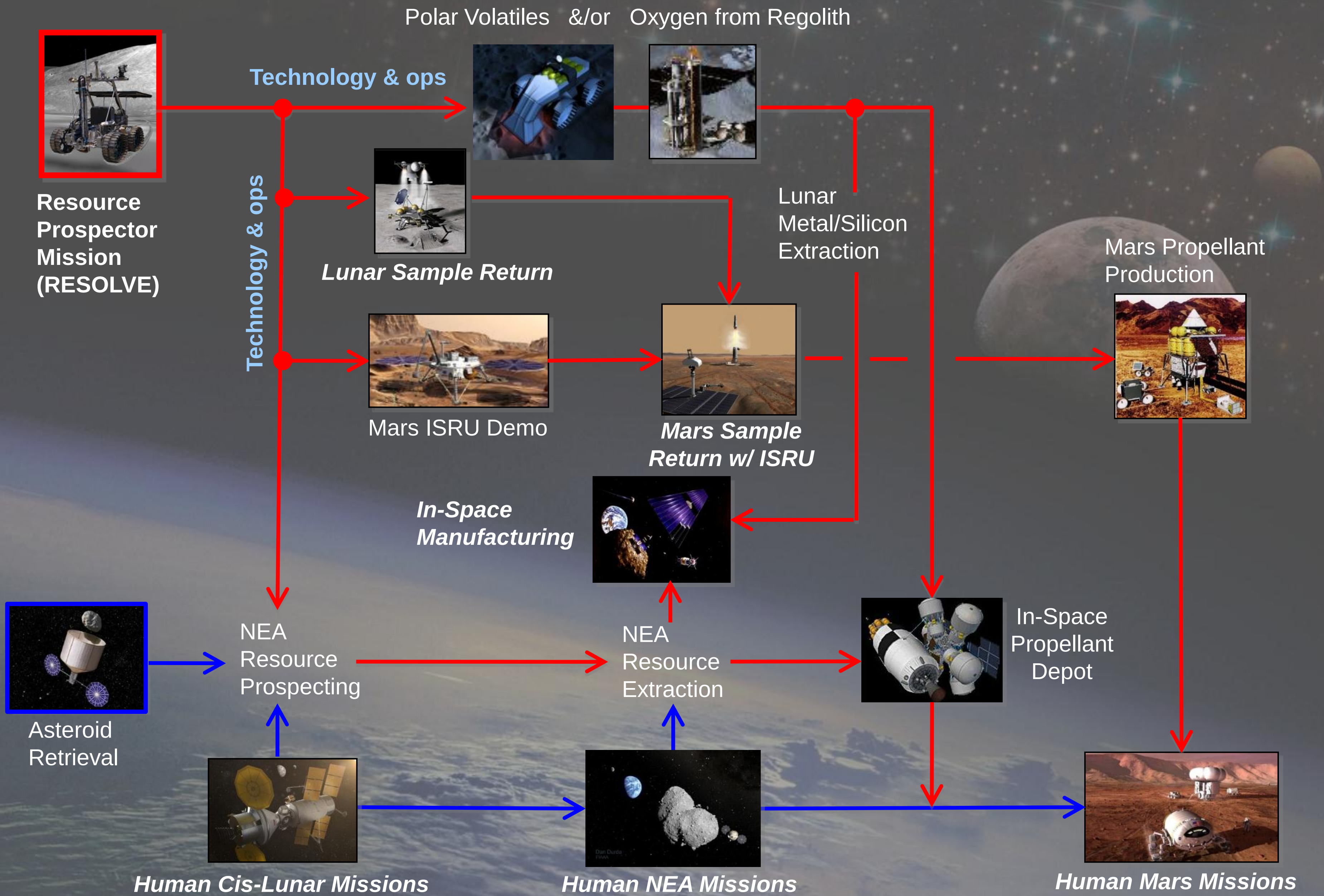


Polar Power 1.1

- 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*

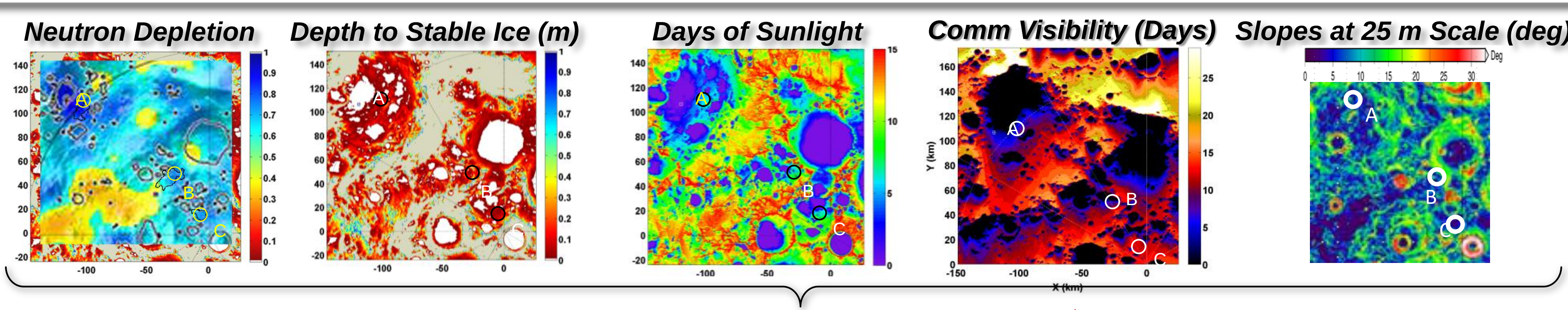
Notional Mission Evolution with ISRU
(for planning)

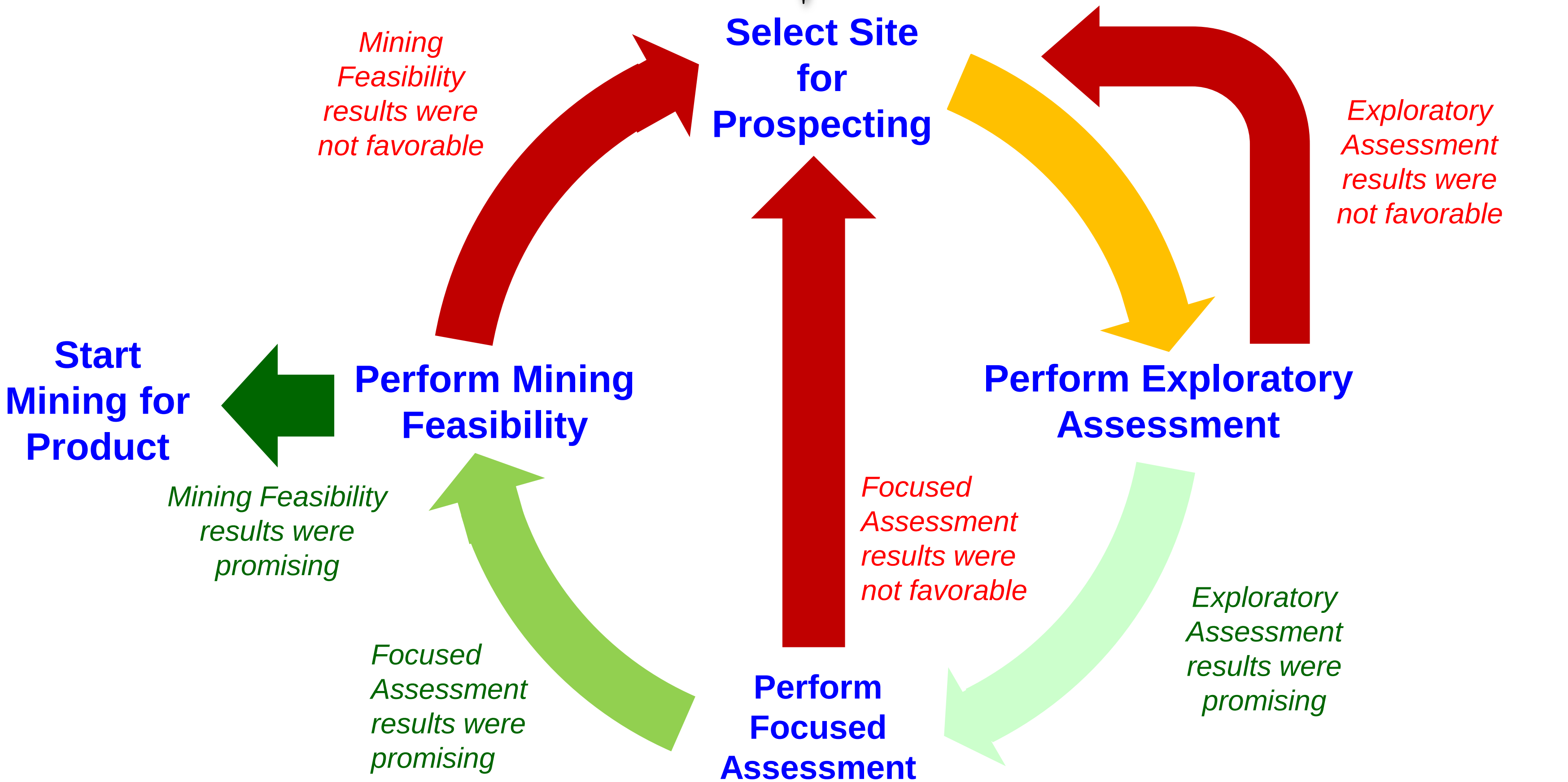


Questions?

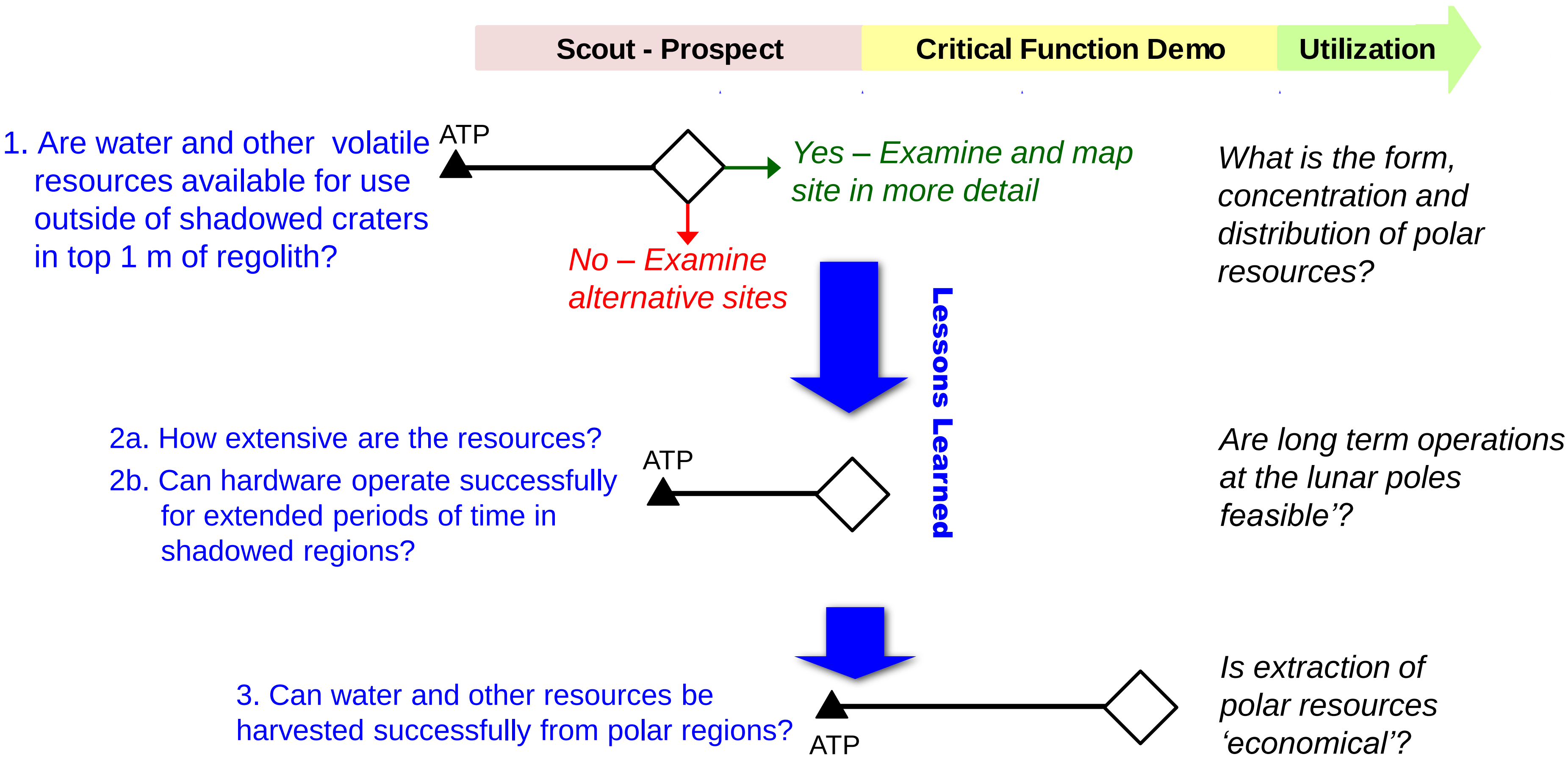
Backup

Lunar Volatile Site Selection - Prospecting Cycle





Approach to Understanding Polar Volatile Resources and Retiring Risk is Required



ATP = Authority To Proceed

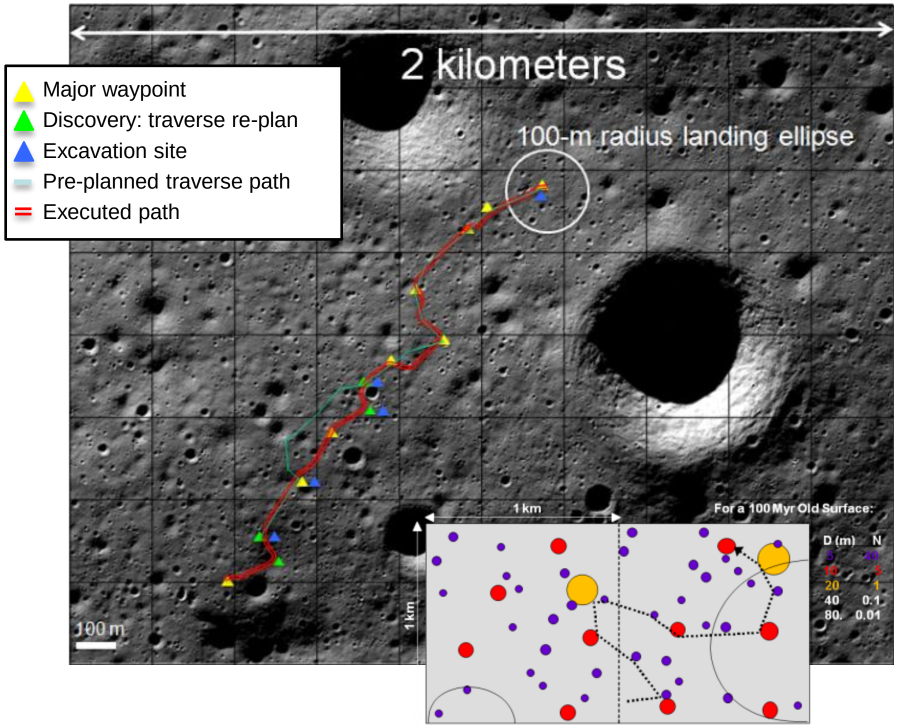
Key RESOLVE Mission Design Trades

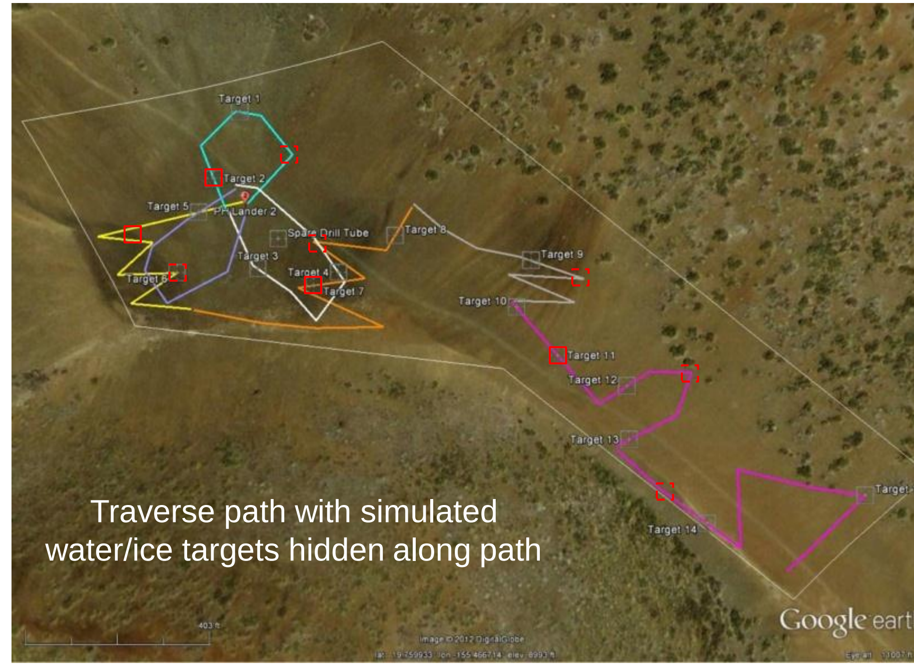
Mission Attributes	Base	Mid	Full
Location	Long duration sunlight	**Min. Sun/Shadowed**	Permanent Shadow
Sample Site Selection	Surface features/minerals	**Neutron Spec on Rover**	Neutron Spec with GPR
Subsurface Sample Acquisition	Arm/scoop	*Auger w sample transer*	**Core Drill/Push Tube w sample transfer**
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

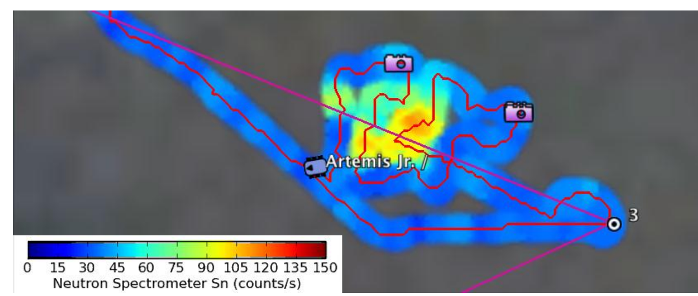
Blue Bold = Baseline

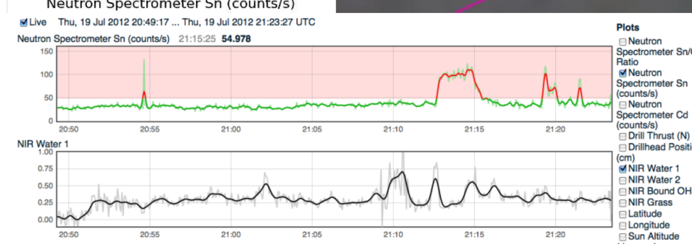
Red Italics = Backup

Exploratory Prospecting for Lunar Volatiles



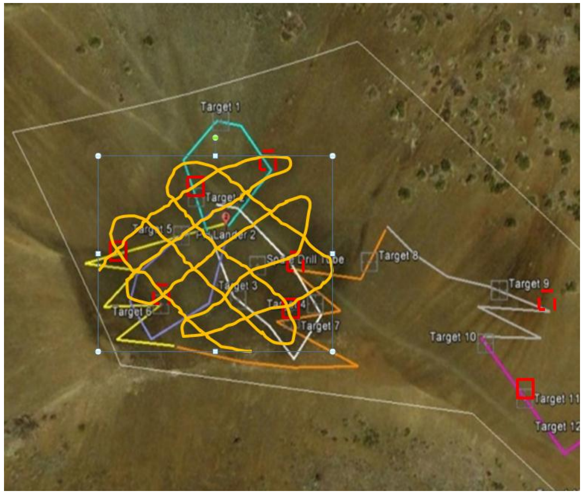






- Hypothesize location of volatiles based global data, terrain, and geological context
- Plan traverse before landing based on location estimates and rover capabilities
- Utilize non-invasive surface and subsurface instruments to guide selection of sample sites; Instrument suite may be limited
- Perform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

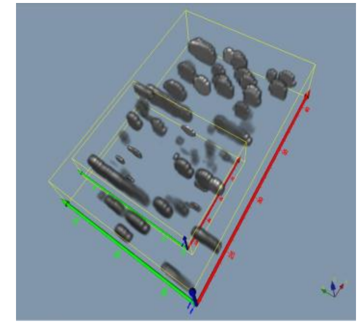
Focused Resource Assessment of Polar Volatiles

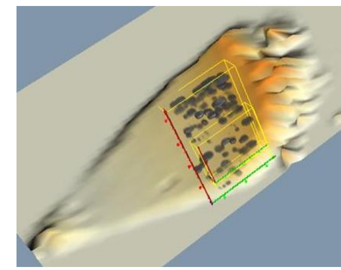


Traverse paths to fill in missing data

Rover-Data localization equipment

Rovers performing coordinated area assessment





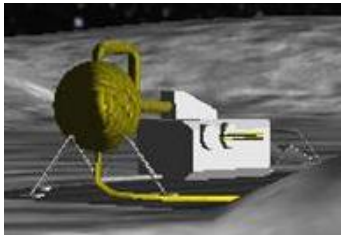
Data fusion with terrain information

- 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

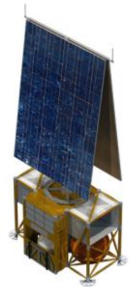
Mining Feasibility for Polar Volatiles

- 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.

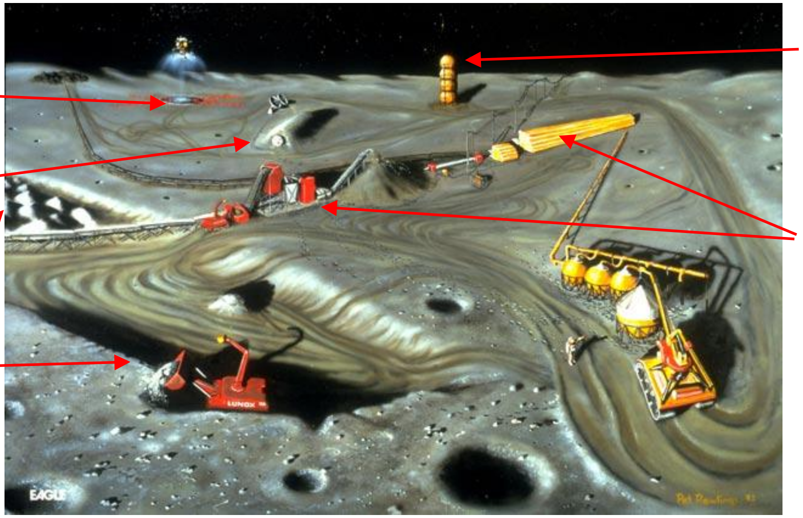
Polar Mobility, Excavation & Processing



Water Plant & Product Storage



Polar Power System

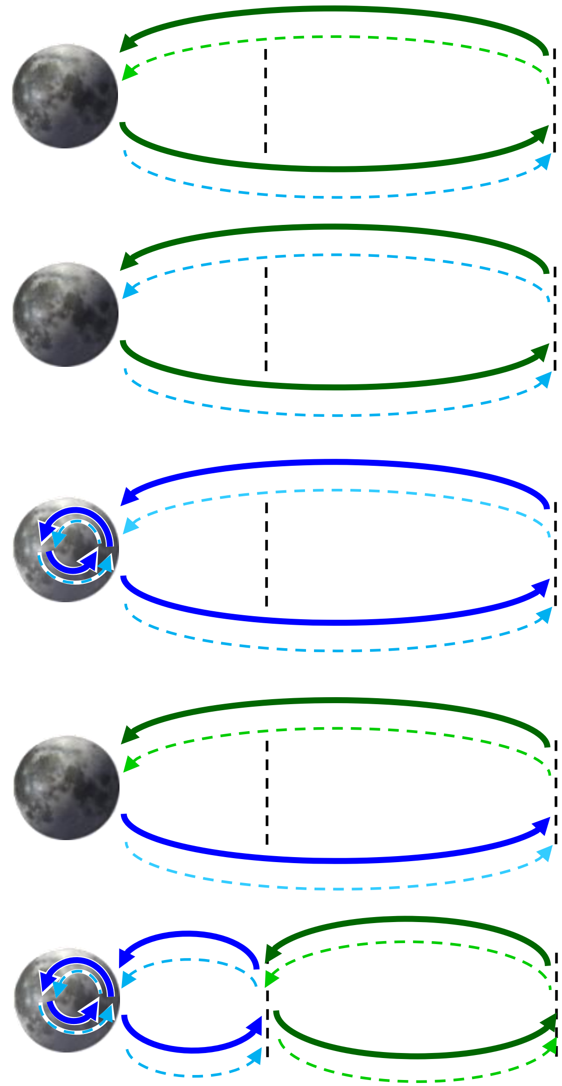


Plan for Mine/Infrastructure Layout & Operation

ISRU and Lunar Transportation Architectures

= Earth Fuel = ISRU Fuel = Earth O_2 = ISRU O_2

Lunar Surface | LLO | L1/L2 Station



Option 1A
Non-Reusable Lander
ISRU O_2 for Ascent
with Earth Fuel

Depot for Earth O_2 & Fuel

Option 1B
Reusable Lander
ISRU O_2 for Ascent/Descent
with Earth Fuel

Depot for Earth Fuel

Option 2: Surface Depot
Reusable Lander
ISRU O_2/Fuel for Ascent/Descent

Option 3: Dual Depot
Reusable Lander
ISRU O_2/Fuel for Ascent
with Earth O_2/Fuel for Descent

Depot for Earth O_2 & Fuel

Option 4: Taxi/Lander Combo to LLO
ISRU O_2/Fuel for Ascent/Descent
with Earth O_2/Fuel for Descent/Ascent

Depot for Earth O_2 & Fuel

Minimum ISRU/Min. Impact
- Supports outpost at any lunar location: Beneficial if returning more than once
- Shared ISRU/Exploration infrastructure
- ~3 MT O_2 for Ascent only
- ~16 MT O_2 for Ascent/Descent

Full ISRU to L1/L2
- Outpost near Poles for O_2 & Fuel Production
- Lander design can be supported by L1/L2 Depot until ISRU is available
- ➢ Global surface access from Outpost
- ~30 MT O_2/H_2 for Ascent/ Descent

Half ISRU to L1/L2
- Outpost near Poles for O_2 & Fuel Production
- 5 MT O_2/H_2 for Ascent/ Descent

Note: ISRU production numbers are only 1st order estimates for 4000 kg payload