3rd International Hawaii-ISRU Analog Field Test

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Space Resources Utilization Changes How We Can Explore Space

Mass Reduction

- >7.5 kg mass savings in Low Earth Orbit for every 1 kg produced on the Moon
- Chemical propellant is the largest fraction of spacecraft mass

Cost Reduction

- Allows reuse of transportation systems
- Reduces number and size of Earth launch vehicles

Space Resource Utilization

Risk Reduction & Flexibility

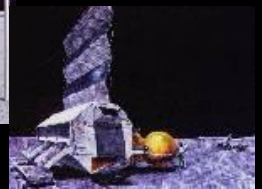
- Provides 'safe haven' capabilities for aborts and delayed cargo resupply
- Radiation and landing/ascent plume shielding
- Increases flexibility and options for contingency and failure recovery operations
- Reduces dependence on Earth

Expands Human Presence

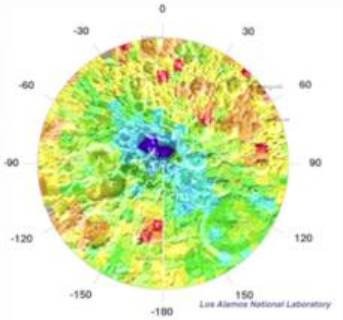
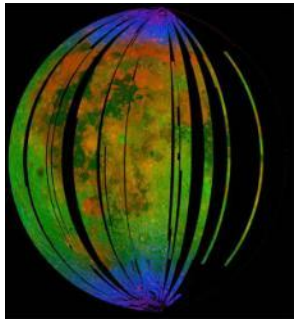
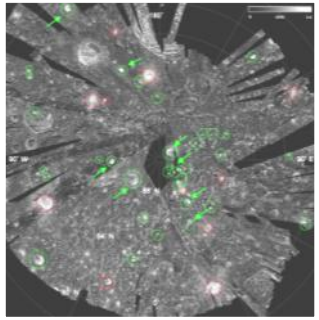
- Increases Surface Mobility & extends missions
- Habitat & infrastructure construction
- Propellants, life support, power, etc.

Enables Space Commercialization

- Provides infrastructure, technologies, and market to support space commercialization
- Propellants, energy, metals, and manufacturing feedstock



What We Know About Volatiles On The Moon

Apollo Samples	Lunar Prospector Lunar Recon Orbiter (LRO)-LEND	Moon Mineralogical Mapper (M^3)	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	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	3 to 10% Water equivalent Solar wind & cometary Volatiles (CO, H_2, NH_3, organics)	Ice layers
Location	Regolith everywhere	Regolith; Apatite	Upper latitudes	Poles	Poles; Permanent shadowed craters
Environment	Sunlit	Sunlit	Low sun angle	Low or no sunlight; Temperatures sustained at <106 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

Why a Lunar Volatiles Prospecting Mission?

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 LCORSS impact site regolith

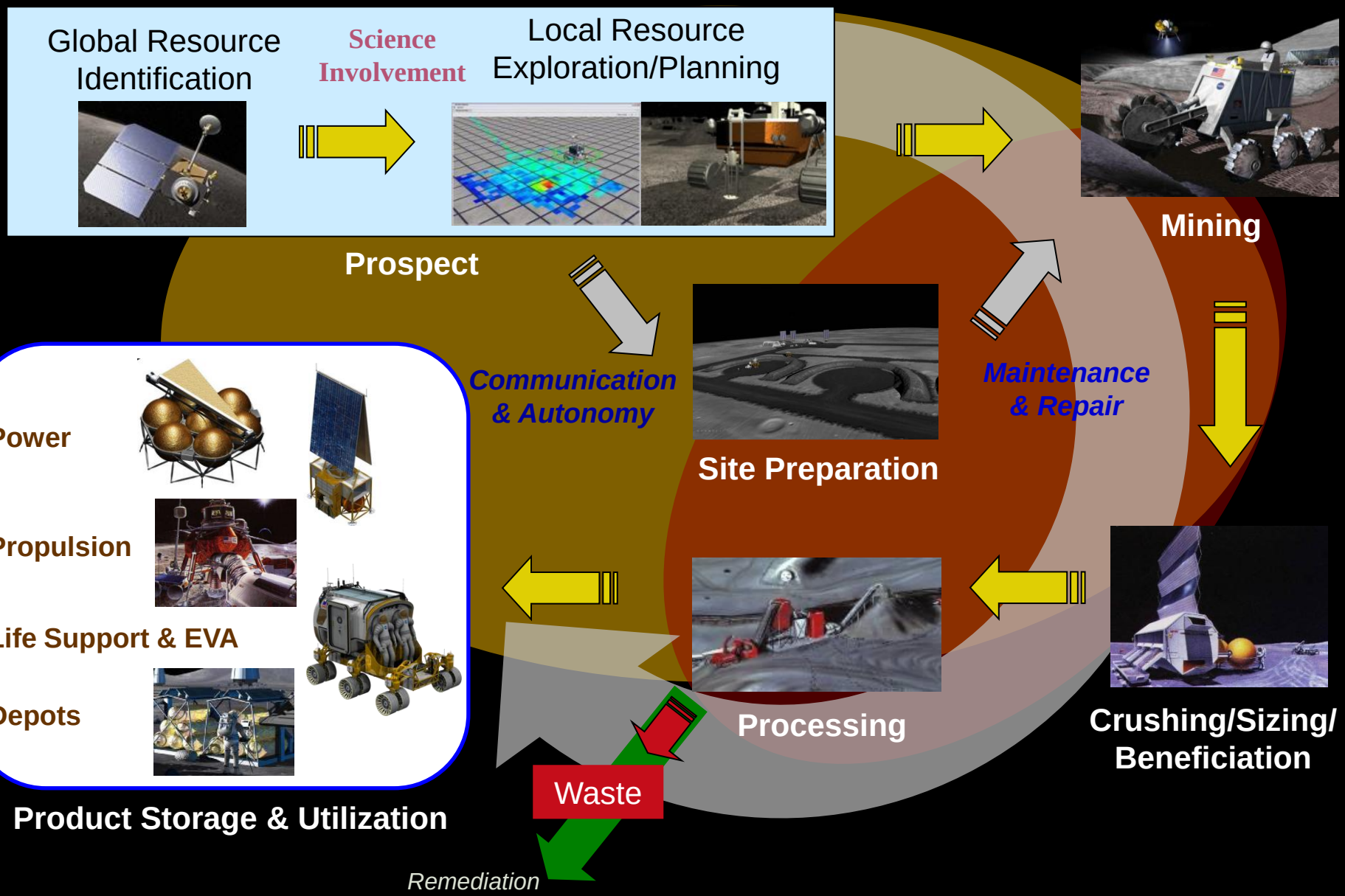
*Chart courtesy of Tony Colaprete

What's the next logical step?

<u>Ground Truth</u>

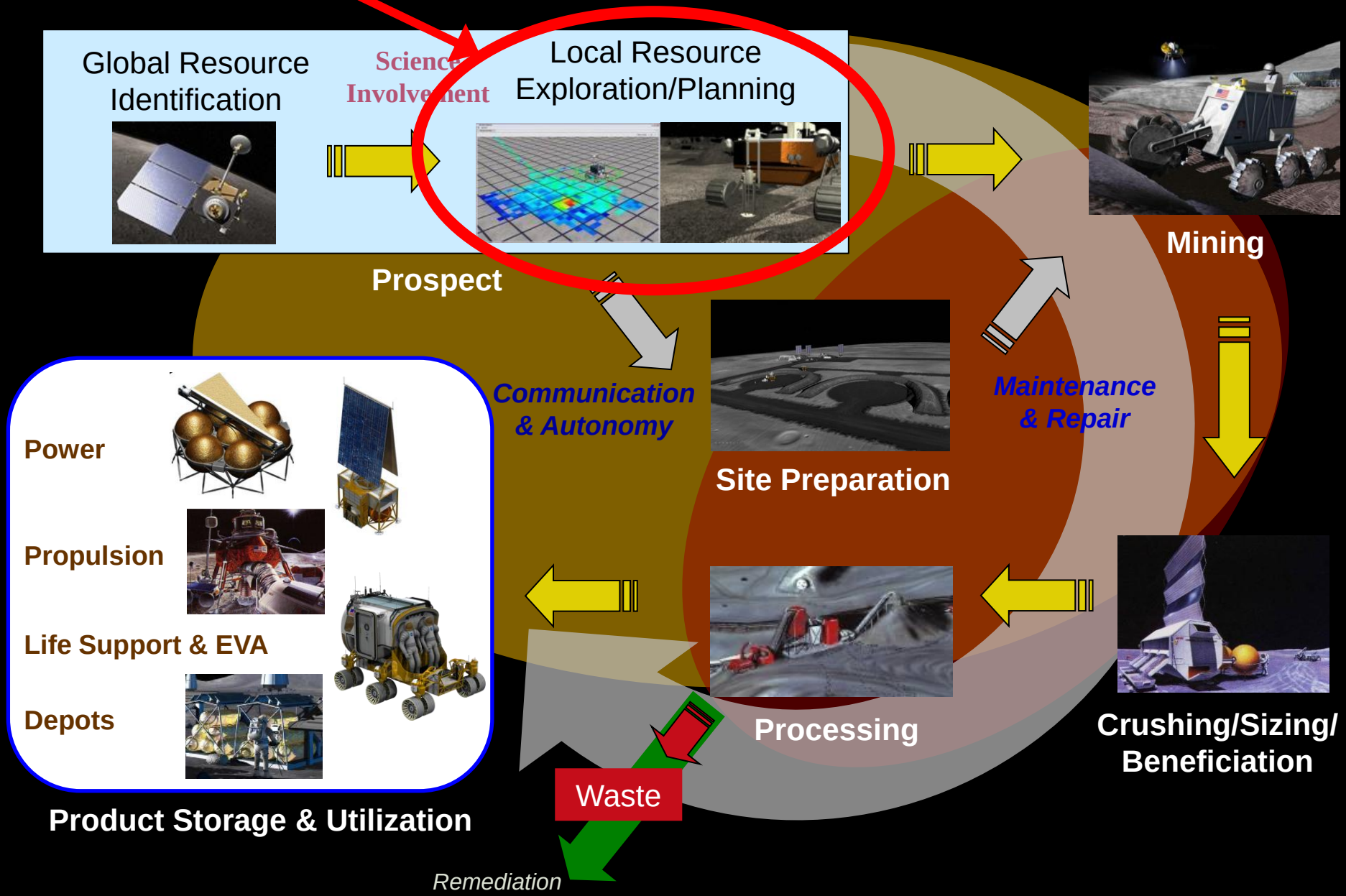
Is this water a resource we can reasonably utilize?

Space 'Mining' Cycle

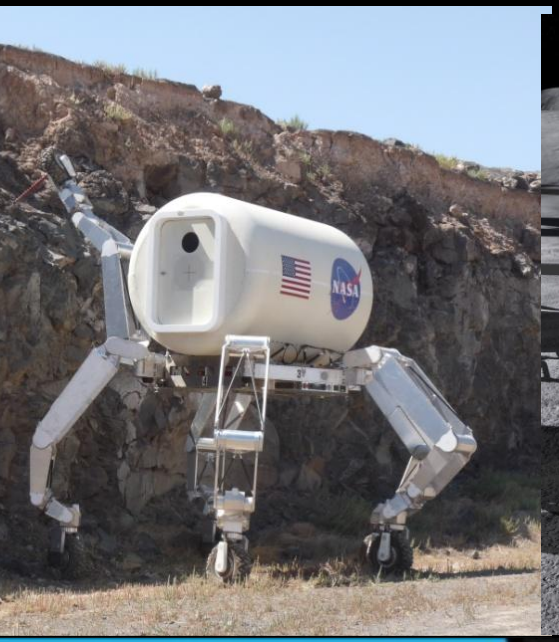


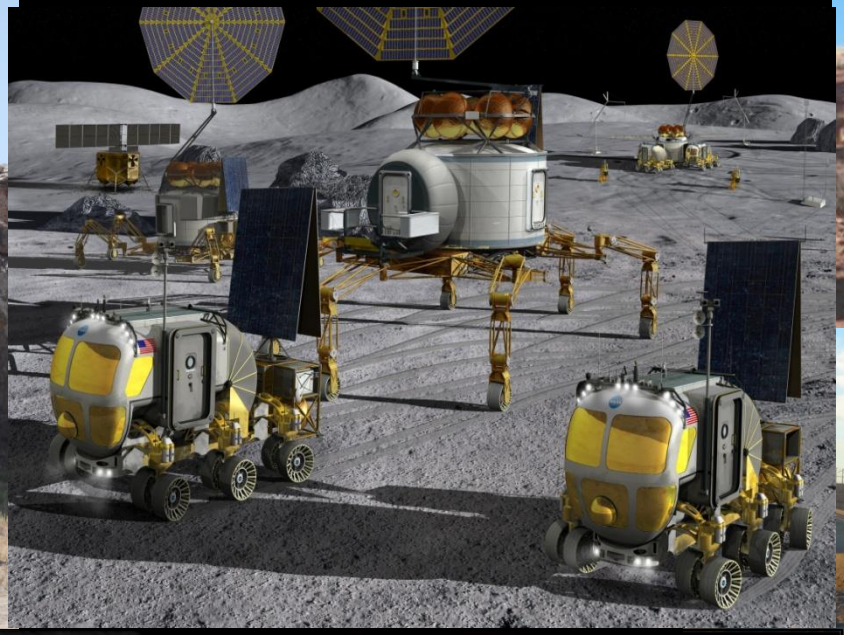
Space 'Mining' Cycle

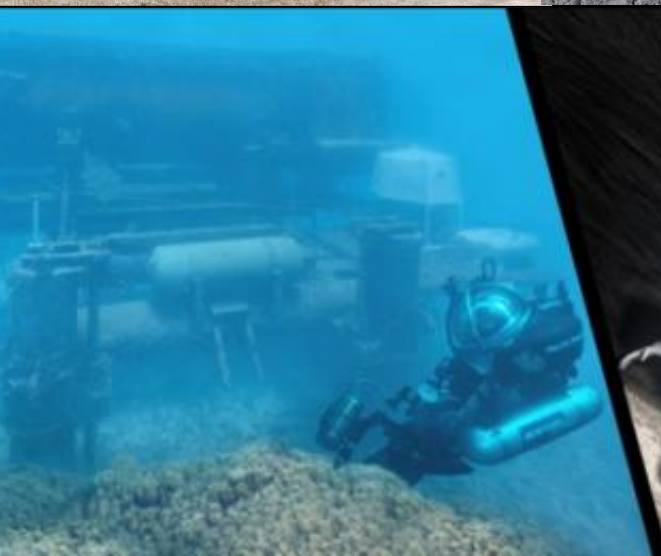
Critical First Step for Moon, Mars, and NEO ISRU missions

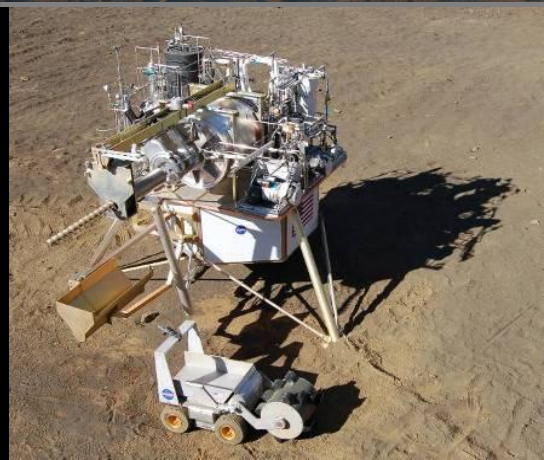


Analog Testing: From Concept to Reality





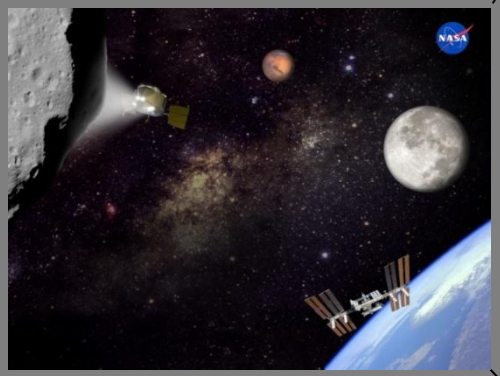




Importance of Analog Field Testing to Prepare for Human Exploration Beyond Low Earth Orbit

Partner Infusion

International, Commercial, Other Government Agencies



Analog Field Tests Validate Key Integrated Architecture Requirements and Concepts

Technology Development
(Energy Storage, Robotics, Human Factors, etc.)

Architecture Element Concept
(Rover, Habitat, Robotics, Power, ISRU, etc.)

Surface Operation/Integration Concepts
(Outpost Maintenance, Exploration, etc.)

Science Concepts
(Site Survey's, Geological Sampling/Curation, etc.)

Crew Training
(Outpost Maintenance, Science, Exploration, etc.)

Outreach & Participatory Exploration
(Web 2.0, Virtual Reality, Simulations, etc.)

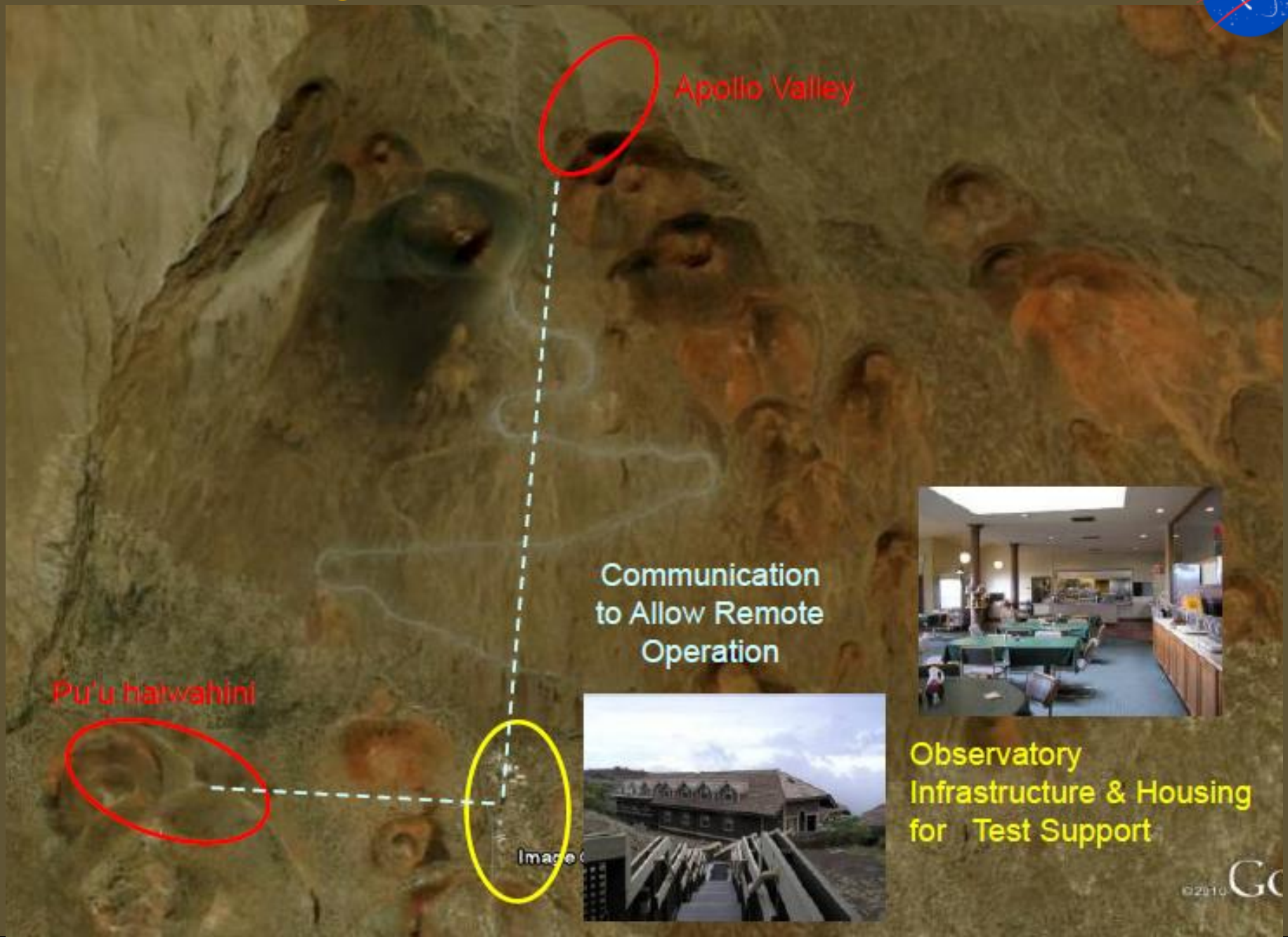
Analog field tests emphasize collaboration between ESMD, SMD, Commercials, OGAs & IPs

Purpose of 3rd International Hawaii-ISRU Analog Field Test

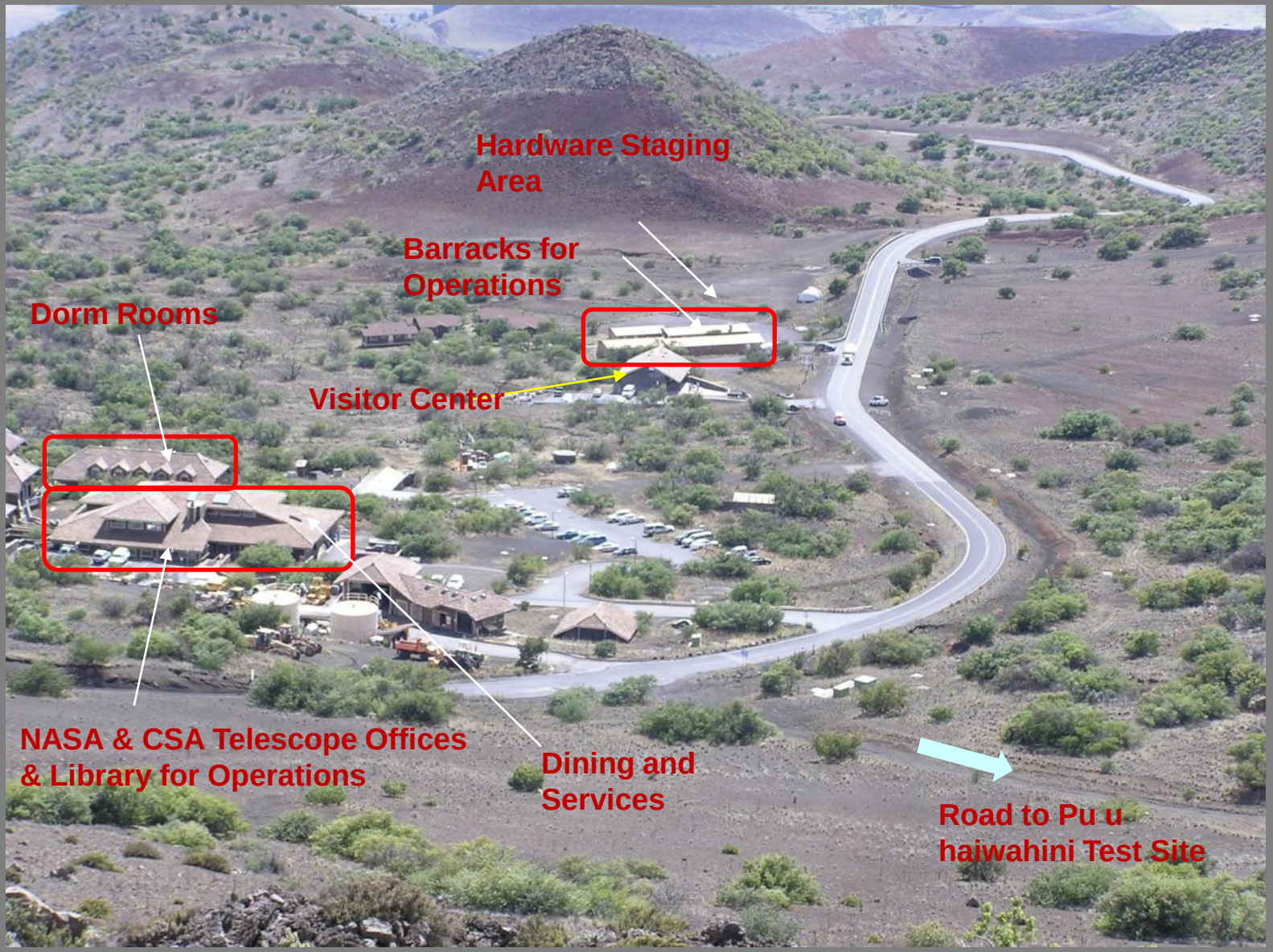
Focus on 1st Step in Space Mining Cycle - Prospect

- **Objective 1:** Demonstrate Integrated Mobility Platform/Science Payload for Lunar Polar Ice/Volatile Mission
  - Water/ice and other volatiles on the Moon can completely change how the Moon is explored and settled
- **Objective 2:** Demonstrate science instruments and operations associated with performing terrain and resource site characterization before crews arrive
  - ISRU Prospecting and Science goals and instruments are synergistic
- **Objective 3:** Demonstrate Mission Support and Operations for Lunar Robotic Precursor
  - Lunar polar missions may be very short (< 7 days) with limited power and communications capabilities

Analog Test Locations on Mauna Kea



Infrastructure At Hale Pohaku



Analog Sites for 3rd Int'l Hawaii Field Testing

'Apollo Valley'

Perform Science/Resource Instrument Operation

- Site has terrain, rock distribution, and soil of interest to polar exploration and has geological diversity of potential interest to science instrument investigators
- Minimal test disturbance required at site
- Tests to be performed with minimum personnel and infrastructure at site; support from Hale Pohaku and Pu'u haiwahini site and remote centers

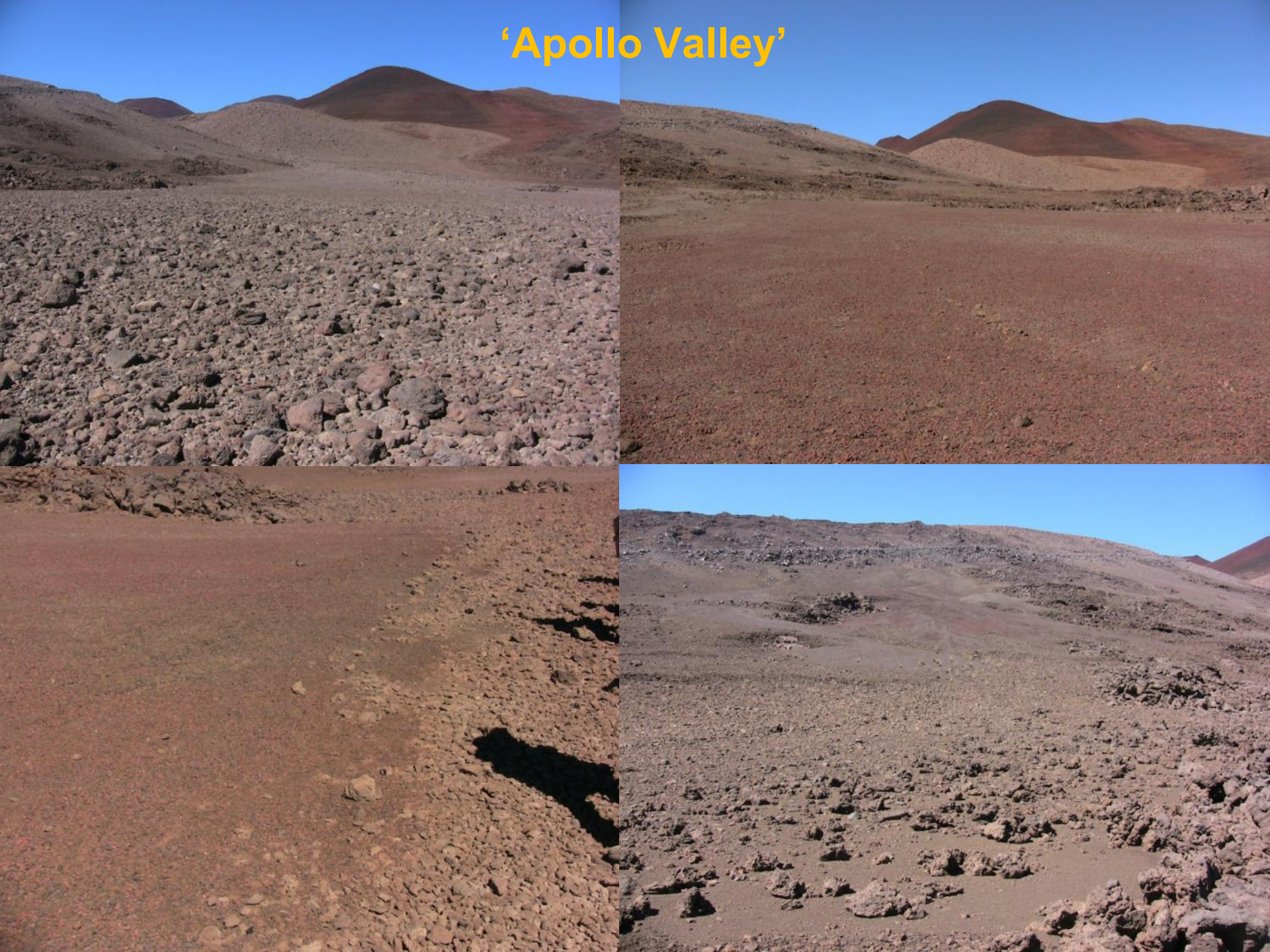
Pu'u haiwahini

Perform Polar Ice/Volatile Mission Simulation

- Site has terrain, rock distribution, and soil of interest to lunar/Mars resource processing, site preparation, and infrastructure integration.
- Site allows for tests involving modification to the landscape: drilling, excavation, etc.
- Tests to be performed with support from Hale Pohaku and remote centers

Test Site on Hawaii Very Much Like the Moon!

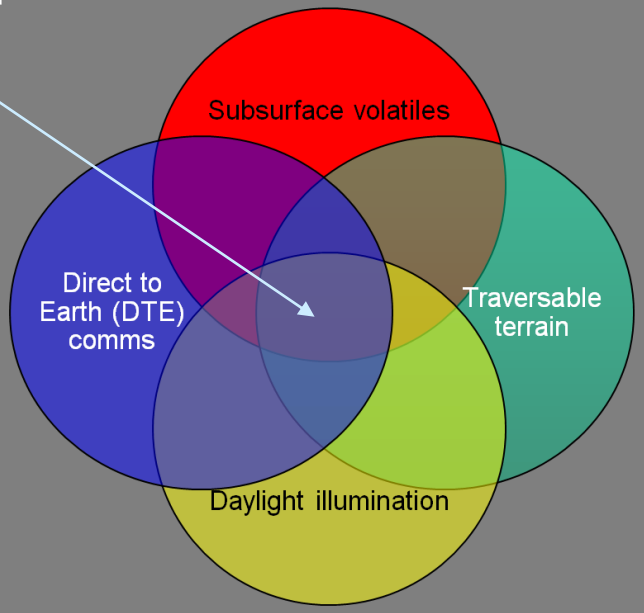
‘Apollo Valley’



Objective 1: Demonstrate Integrated Mobility Platform/Science Payload for Lunar Polar Ice/Volatile Mission

Mission Overview

- Polar landing site based on meeting following four criteria
  1. Direct view to Earth for communication
  2. Sunlight for duration of mission for power
  3. Subsurface Volatiles
     - High hydrogen content (LRO LEND instrument)
     - Constant <100 K temperatures 10 cm below surface (LRO Diviner instrument)
  4. Reasonable terrain for traverse
- Three preliminary locations were identified at the north and south pole to define mission and hardware requirements



Mission Simulation Purpose:

Perform mission scenarios remotely with all hardware/capabilities required

- Demonstrate integration (physical, data, power, command) of all hardware necessary for flight mission on mobile platform(s)
- Demonstrate integrated operations of RESOLVE and rover hardware and software
  - Roving / Scanning
  - Drilling / Sample Transfer
  - Sample Processing / Discarding
- Demonstrate all mission operations and timelines to validate short duration lunar mission
  - Simulate a polar volatiles design reference mission from landing through lunar 'sunset'
  - Demonstrate pre-mission planning and real-time re-planning of field demo
  - Demonstrate effective operations control team
- Demonstrate mission command and control (with lunar time delays and bandwidth limitations)

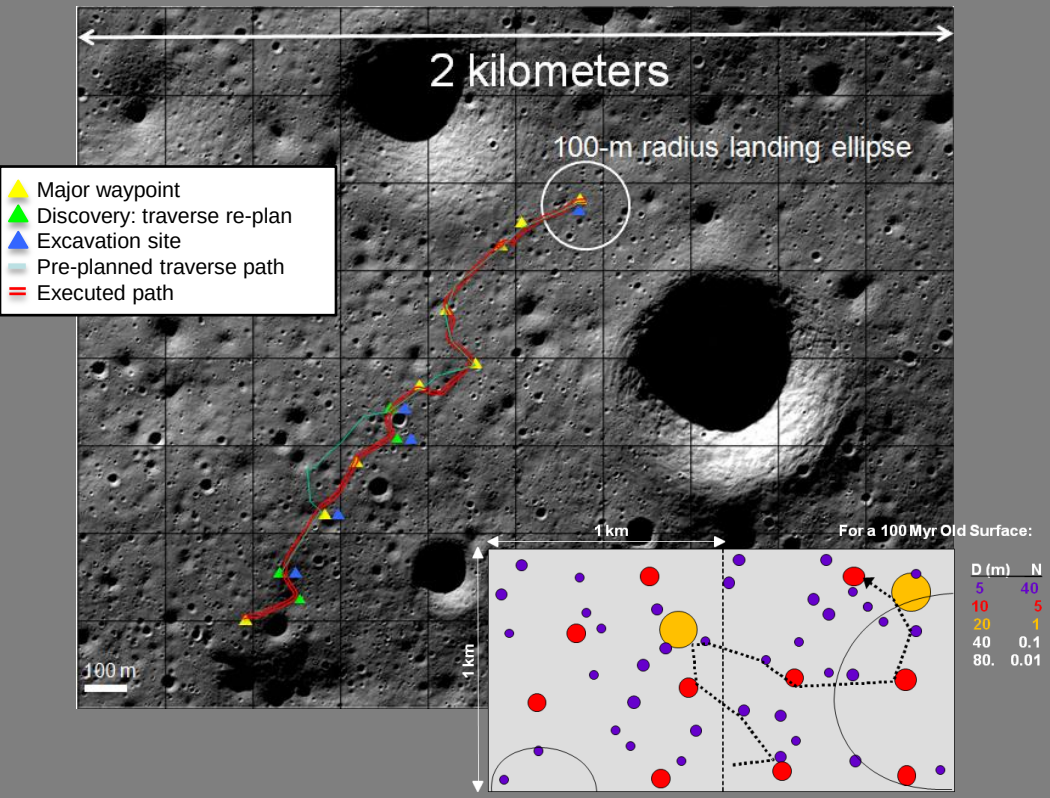
Lunar Polar Ice/Volatile Mission Objectives

CAT 1 Objectives (Mandatory)

1. Travel at least 100m on the lunar surface to map the horizontal distribution of volatiles

CAT 2 Objectives (Highly Desirable)

1. Perform at least 1 coring operation. Process all regolith in the drill stem acquired during the coring operation.
2. Perform at least 1 water droplet demo during volatile analysis.



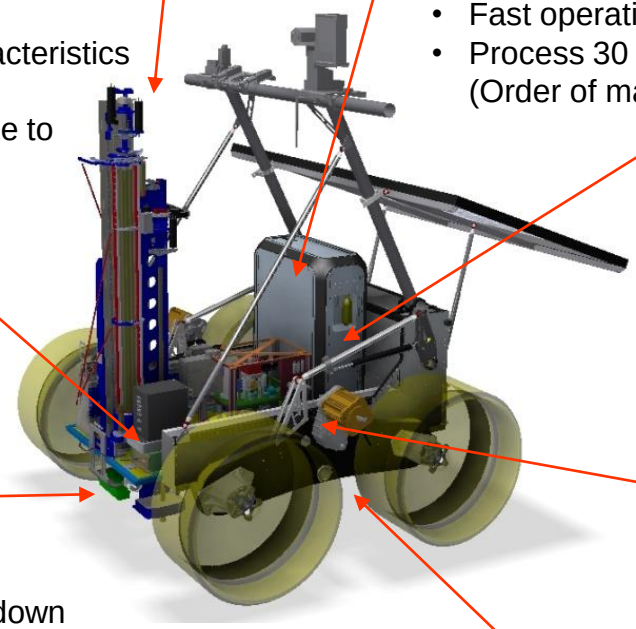
CAT 3 Objectives (Desirable)

1. Map the horizontal distribution of volatiles over a point to point distance of 500m (lunar objective is 1km.)
2. Perform coring operations and process regolith at a minimum of 3 locations.
3. Volatile analysis will be performed on at least 4 segments from each core to achieve a vertical resolution of 25cm or better.
4. Perform a minimum of 3 Augering operations (Note that the Lunar objective is 6)
5. Perform at least 2 total water droplet demos. Perform 1 in conjunction with hydrogen reduction and perform 1 during low temperature volatile analysis.

CAT 4 Objectives (Goals)

1. Perform 2 coring operations be separated by at least 500 m straight line distance. (lunar objective is 1km.)
2. Travel 3 km total regardless of direction
3. Travel directly to local areas of interest associated with possible retention of hydrogen
4. Process regolith from 5 cores
5. Perform hardware activities that can be used to further develop lunar exploration technologies

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



Subsurface Sample Collection –

Auger/Core Drill [CSA]

- 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 Design Characteristics

- Nom. Mission Life = 10+ Cores
- Mass = 60-70 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]

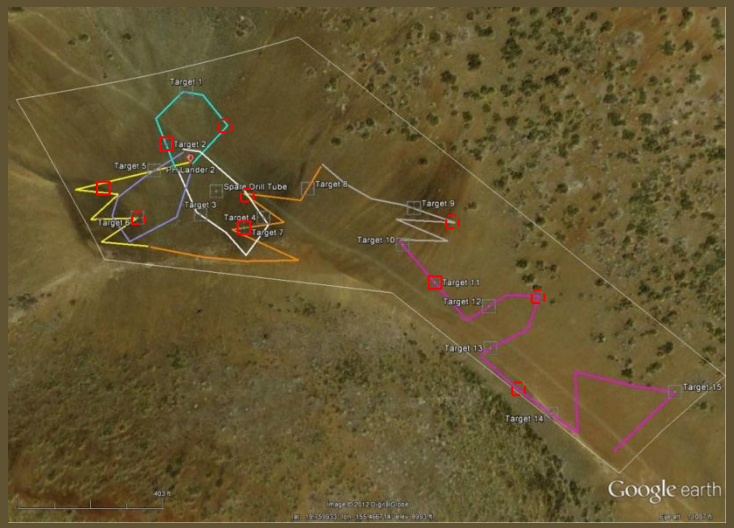
- Space-rated microprocessor

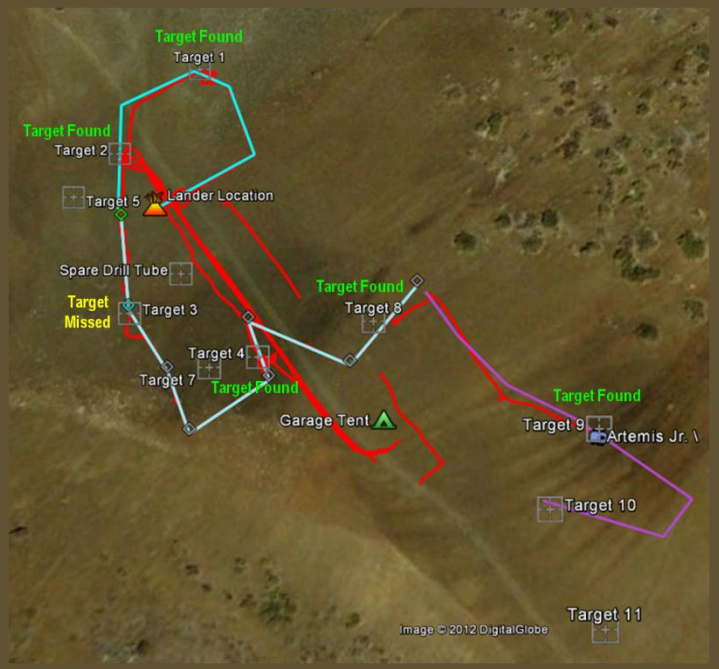
Surface Mobility/Operation [NASA/CSA]

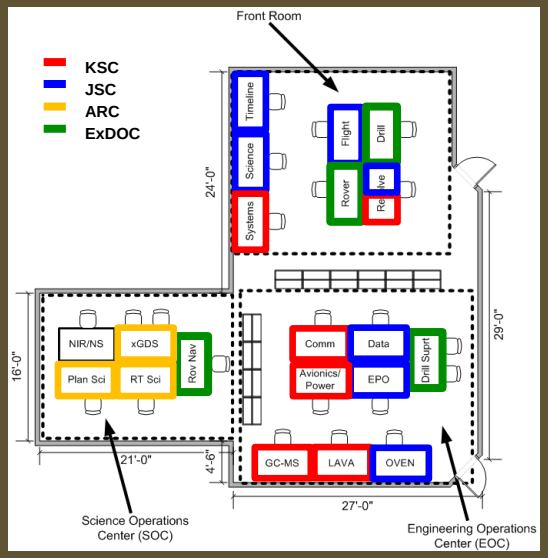
- Low mass/large payload capability
- Driving and situation awareness, stereo-cameras
- Autonomous navigation using stereo-cameras and sensors

Lunar Polar Resource Mission Simulation

Traverse path with simulated water/ice targets



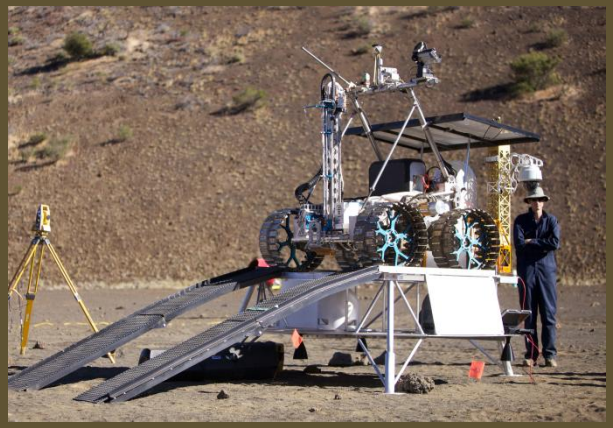




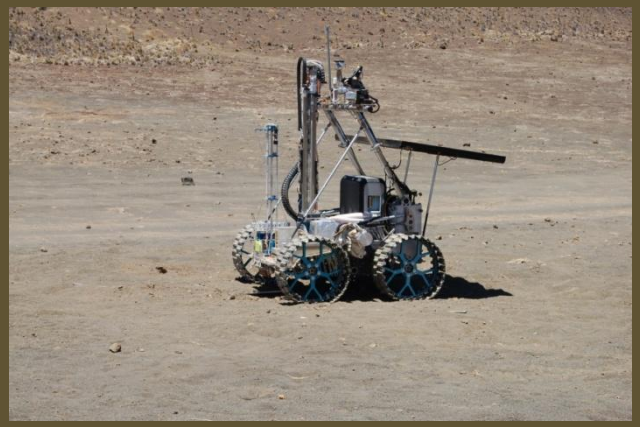
'Flight control' rooms in Hawaii, Houston, Kennedy, and Montreal. Science room at Ames

Lunar Polar Resource Mission Simulation

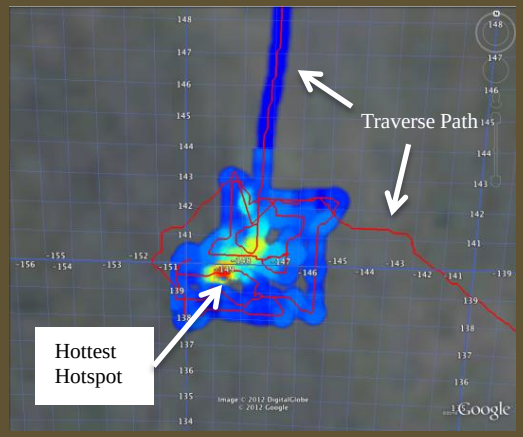
‘Flight’ like hardware and operations



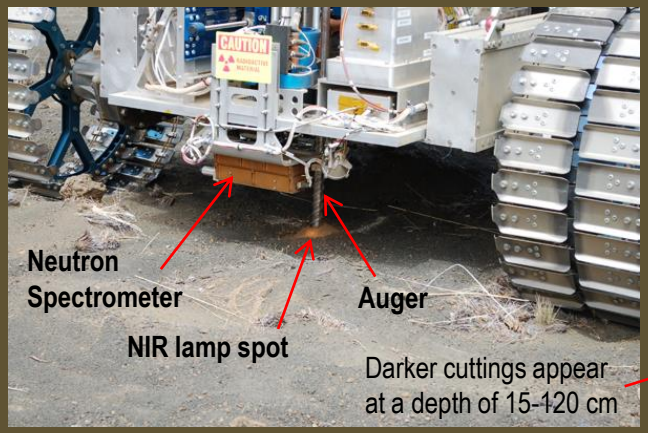
Rover Egress from Lander

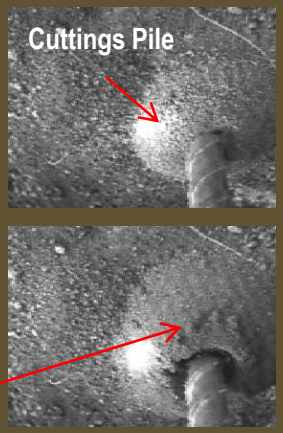


Rover Searching Exploration Site



Data from Neutron Spectrometer and Rover Navigation displayed on xGDS showing ‘hot spot’ found by RESOLVE





Auger and Examine Cutting Pile for Ice with Near Infrared Spectrometer

Drilling, Sample Collection, Sample Transfer, & Processing to Measure Water and Other Volatiles

Objective 2: Demonstrate Instruments and Science Operations

Mission Goal: Test potential science operations architecture that would provide geologic history and context to support rapid resource location and characterization.

Geologic Context means: Where at the site were conditions (as recorded in the rock record) favorable for resource deposition?
Geologic History means: When were those conditions prevalent and when did they cease?

Mission Overview: 3 Days of Field Operations

- Day 1 - GPR operations are primary focus
- Day 2 - Mössbauer operations are primary focus
- Day 3 - Operations based on previous days' results
- Samples collected for VAPoR & MeSH instruments throughout mission simulation

Mission Simulation Purpose:

- Evaluate performance and effectiveness of Science Mission Directorate (SMD) Moon Mars Analog Mission Activity (MMAMA) instruments.
- Evaluate operation concepts and instrument effectiveness in characterizing geologic context and history, site terrain and physical/mineralogical properties of potential resources.

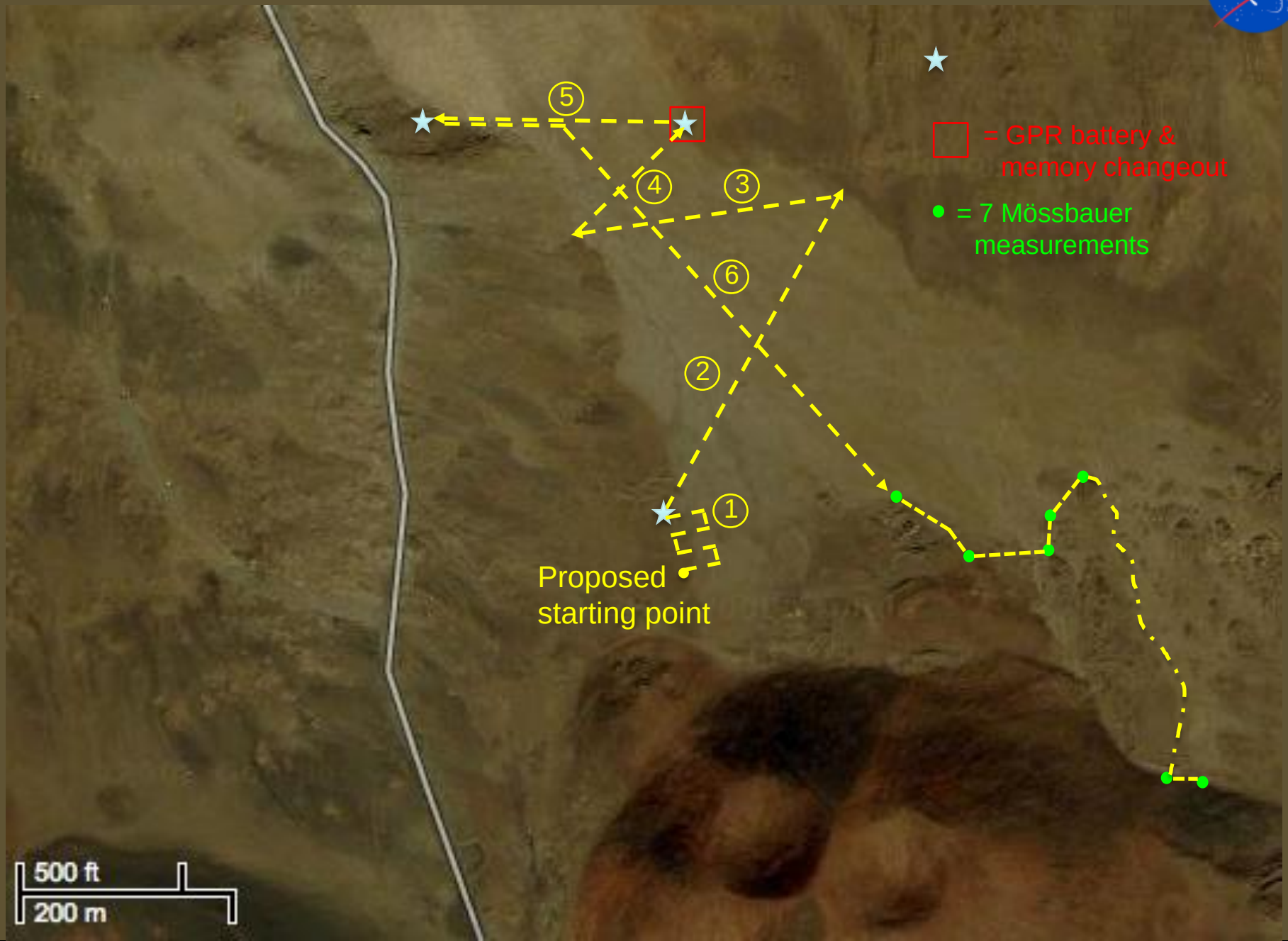
Objective 2: Demonstrate Instruments and Science Operations (2 of 2)

Instruments

- Ground Penetrating Radar (GPR)
- Mössbauer/X-Ray Fluorescence
- Mechanized Sample Processing and Handling System (MeSH)
- Volatile Analysis by Pyrolysis of Regolith (VAPoR)
- Imagers
  - Panoramic video camera (Lucy)
  - Digital Microscope
- Mission Support Instruments
  - Magnetic susceptibility meter
  - Combined altimeter and 3-axis accelerometer
  - GPS location sensor

Apollo Valley Science Operations

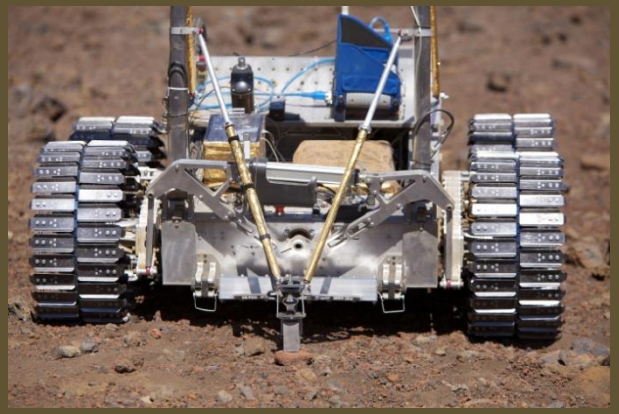
Apollo Valley Science Field Test Traverse



Science Operation and Resource Characterization Test Activities

Instrument Integration and Checkout on Juno II rover

Ground Penetrating Radar operation in Apollo Valley



Mössbauer operation in Apollo Valley

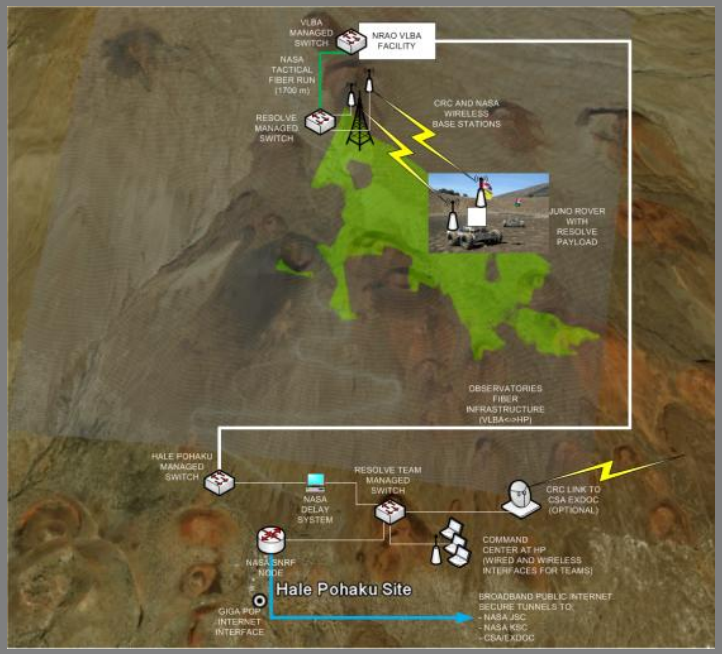
Personnel in Apollo Valley

Science Operations at Hale Pohaku

Objective 3: Demonstrate Mission Support and Operations for Lunar Robotic Precursor

Purpose: Utilize mission representative communications infrastructure and remote operation centers and procedures

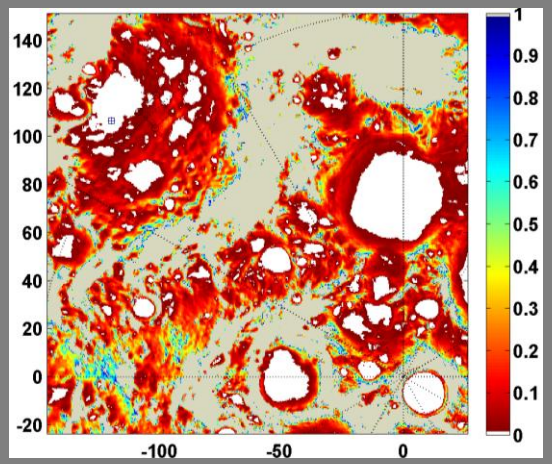
- Control and limit bandwidth and introduce communication delays and noise for rover and payload to simulate communication challenges for lunar polar mission
- Utilize remote operations centers at CSA Headquarters, NASA (ex Shuttle/ISS control rooms) and other participants for field test operations (after initial operations performed near test site)
- Utilize SNRF communication architecture between centers to minimize firewall issues
- Utilize ISS/MSL planning tool (Score/Playbook) and establish remote operations teams for hardware and science



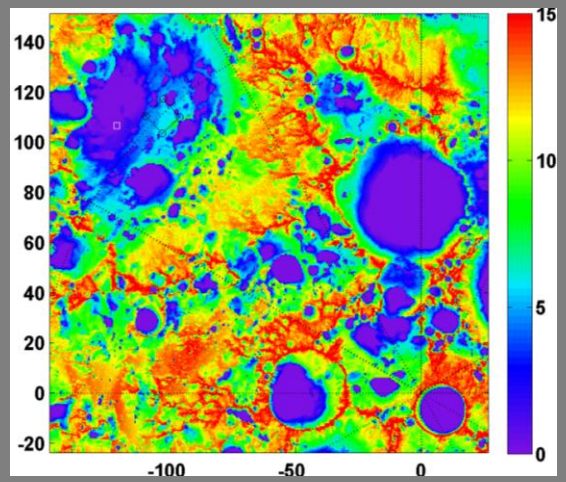
Backup

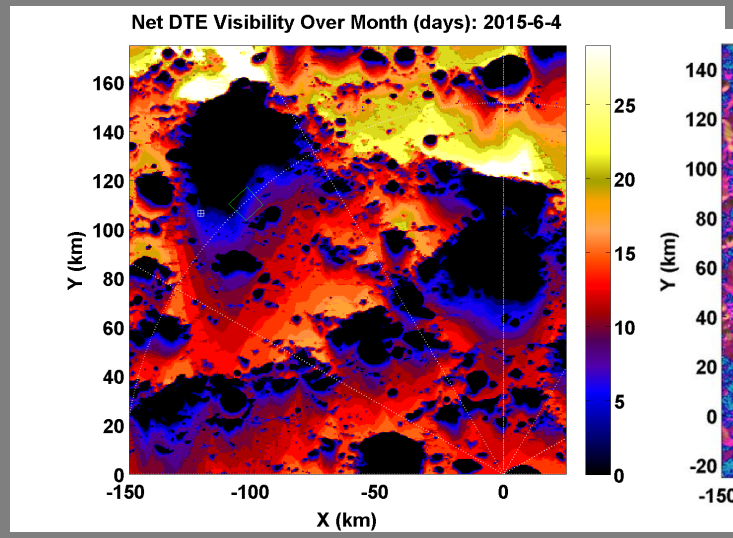
RESOLVE Mission Options
Potential South Pole Landing Sites (Summary)

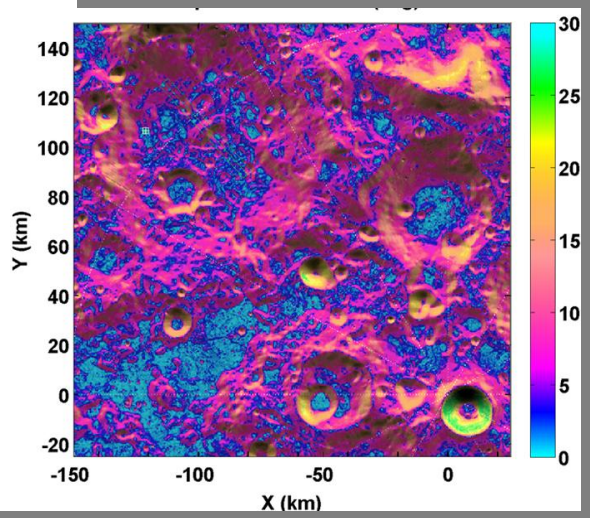
Combined Site Analysis



Site:	A	B	C
Shallow “Frost Line”	<0.1 m	<0.2 m	<0.1 m
Slopes	<10°	<15°	<10°
Neutron Depletion	4.5 cps	4.7 cps	4.9 cps
Temporary Sun*	4 days	2-4 days	5-7 d
Comm Line of Sight*	8 days	17 days	17 days
* may not coincide			







3rd ISRU Analog Operations Objectives

- **Primary Operations Objectives**
  - Successfully complete science and engineering based mission objectives through remote operations
    - Roving / Mapping
    - Drilling / Sample Transfer
    - Sample Processing / Analysis
  - Successfully operate with lunar-like communications, power, and other operational constraints
    - Uplink (10 kbps) and downlink (380 kbps) bandwidth
    - 1.7 second communications delay each direction
    - Optimize power timeline to reduce total energy needs and peak powers
  - Demonstrate pre-mission planning and real-time re-planning of field demo timeline
    - Develop tools and products for the real-time execution of a mission
      - xGDS, Score
      - Flight Rules, Procedures, and Training Material
  - Demonstrate effective operations control team
    - Coordination of multiple participants in multiple locations
    - Develop mission decision making hierarchy for flight control and management teams
    - Develop control center architecture: console positions, voice loops, console tools, etc needed for lunar mission
  - Collect inputs on the flight control team's needs for real-time data viewing, manipulation, recording, and distribution
    - Define operations, software, and display requirements for lunar mission

- **Secondary Operations Objectives**
  - Characterize the time required for various mission activities to help refine future timelines
  - Demonstrate end-to-end integrated operations of RESOLVE hardware and software