

Using Analog Field Tests To Link and Prepare Science and In-Situ Resource Utilization for Future Space Missions

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Abstract

A major goal of NASA's human exploration program is to learn how to use the resources of space, known as In-Situ Resource Utilization (ISRU), to lower the cost and risk of human space exploration. Successful implementation of ISRU requires detailed knowledge of surface and subsurface materials, minerals, and volatiles that may be present. This same information is required to better understand the physical and geologic composition, structure, origin, and evolution of the Moon, Mars, and other extraterrestrial bodies of interest. It is also important to recognize that while ISRU and science objectives may be similar, the desired method or hardware to achieve the information desired may be drastically different. One method to promote understanding, coordination, and joint development of instruments and operations between Science and ISRU is the use of analog field demonstrations.

1. Introduction

For the last four years, NASA has performed a series of human lunar exploration studies, including the Lunar Architecture Team Phase I and II, the Constellation Architecture Team Trade Space 1, 2, & 3, and several Lunar Surface System mission scenarios. In July of 2008, the 14 international space agency members of the International Space Exploration Coordination Group agreed to collectively explore ideas and plans for human exploration of the Moon as a first step in jointly defining objectives and mission scenarios, with the goal of defining a global reference architecture for human lunar exploration by mid 2010. While performing significant lunar science has always been a major goal for all of these studies, the exact science performed and how it integrates into other human exploration activities has rarely been part of the main stream effort. Separate parallel studies and workshops, such as the NASA Advisory Council (NAC) "Workshop on Science Associated with the

Lunar Exploration Architecture" in 2007, have been used to help prioritize science goals and objectives and how they relate to the on-going human exploration architecture studies. What is clear from the results of both of these efforts is that there is not only significant overlap and synergism between the goals and objectives for science and exploration, but that with proper planning and development, efforts in one can enable new objectives in the other, and vice versa. However, it is also clear that further efforts are required to link the separate Science and Exploration architecture and mission planning activities.

2. ISRU and Science

ISRU involves the understanding, collection, manipulation, and processing of local material into products for robotic and human exploration, such as propellants, fuel cell reactants, life support consumables, thermal energy storage, and hardware/crew protection. To obtain these products, ISRU processes that may be incorporated into missions include extracting water and other volatiles from lunar permanently shadowed craters and Mars soil, extracting oxygen from lunar regolith minerals, processing the Mars atmosphere into oxygen and fuel, and performing civil engineering and construction tasks. Successful implementation of ISRU requires detailed knowledge of the type and distribution of resources that may be of interest, understanding of the potential impurities that could foul processing, and knowing the physical attributes of the planetary material to ensure excavation, material transport, and processing systems are designed properly. This requires the development and use of hardware and instruments for orbital and local mineral characterization, access to surface and subsurface materials, material processing to characterize volatiles and make products, and methods for evaluating process efficiency. Hardware, instruments, and operations for ISRU are all common with science goals and objectives associated with determining the

physical and geologic composition, structure, origin, and evolution of the lunar crust and subsurface as well as the location, distribution, and movement of solar, bombardment, and endogenous lunar volatiles. The implementation of ISRU for exploration can support and enable lunar science objectives ‘Of the Moon’, ‘On the Moon’, and ‘From the Moon’, while conversely science instruments and measurements are critical to understanding lunar resources, their distribution, and how to extract and process these resources with the minimum of development and implementation risk for human exploration. Similar synergism exists between ISRU and “Follow the Water” science objectives for Mars.

3. The Role of Analog Testing

In the constant reality of limited budgets, it is imperative that ISRU objectives, development, and implementation into robotic and human missions be coordinated and executed with scientific investigations. However, it is also important to recognize that while overall objectives may be the same, the desired method or hardware to achieve these objectives may be drastically different. One method to promote understanding, coordination, and joint development of instruments and operations in the near term is the use of analogue field demonstrations. Analog field demonstrations allow for evaluation of technologies and operations under reasonably realistic conditions. They also allow for independent development of instruments and technologies to common operation and mission needs. Technologies and operational procedures from both science and exploration can be added when available on a continuing basis of evolving overall integrated operations and capabilities that can be utilized in future flight missions. Performing analog tests with personnel from both ISRU and science together allows both sides to better tailor their instruments and operations to meet overall mission needs with the minimum of resources. It also demonstrates integration and operational procedures well in advanced of robotic precursor missions.

4. ISRU-Related Analog Field Tests

ISRU-related analog field tests are based around the ‘Theme’ of demonstrating the Lunar ISRU Cycle (Figure 1). To begin to understand how best to integrate, coordinate, and operate ISRU, mobility, and science hardware and systems for a future

robotic mission to characterize polar volatiles on the Moon, a lunar analog field test was held in November, 2008 on Mauna Kea in Hawaii. The field test involved integration of the Regolith & Environment Science and Oxygen & Lunar Volatile Extraction (RESOLVE) experiment onto the Scarab rover. This first field test was successful in demonstrating several key aspects of a future robotic lunar polar mission including: autonomous dark navigation, semi-autonomous drill site selection, 6 core drilling and sample transfer operations, 6 sample volatile analysis cycles, 4 subscale oxygen extraction from regolith demonstrations, and use of Raman and Moessbauer spectrometers to evaluate mineral characteristics before and after processing.

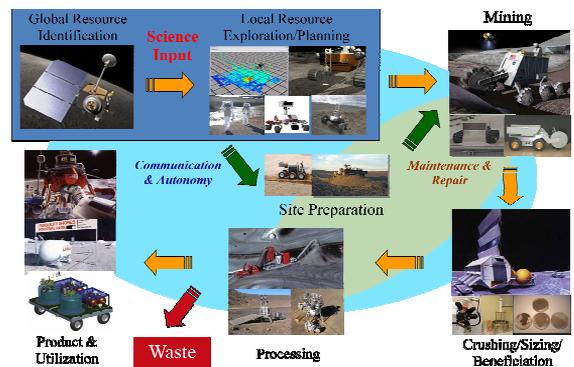
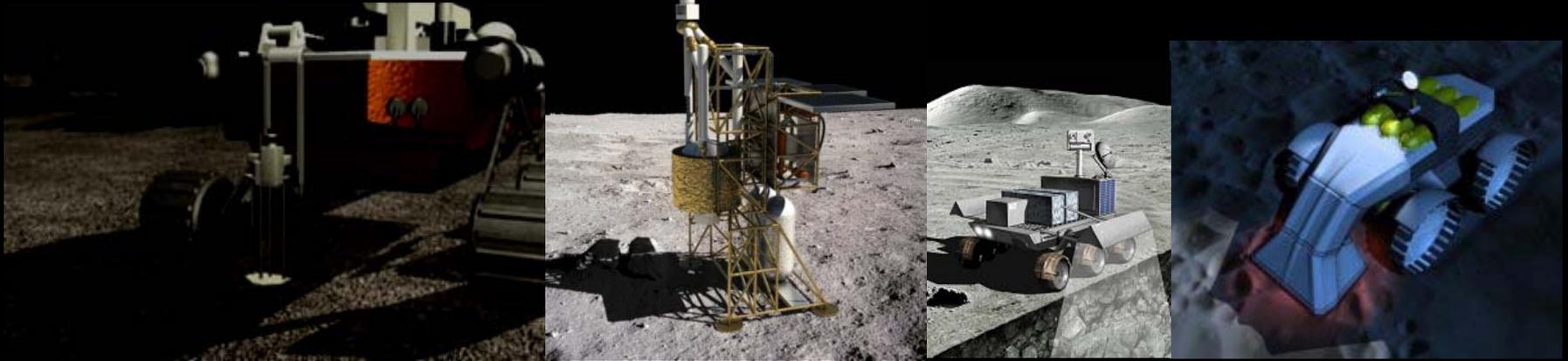


Figure 1: Lunar ISRU Cycle

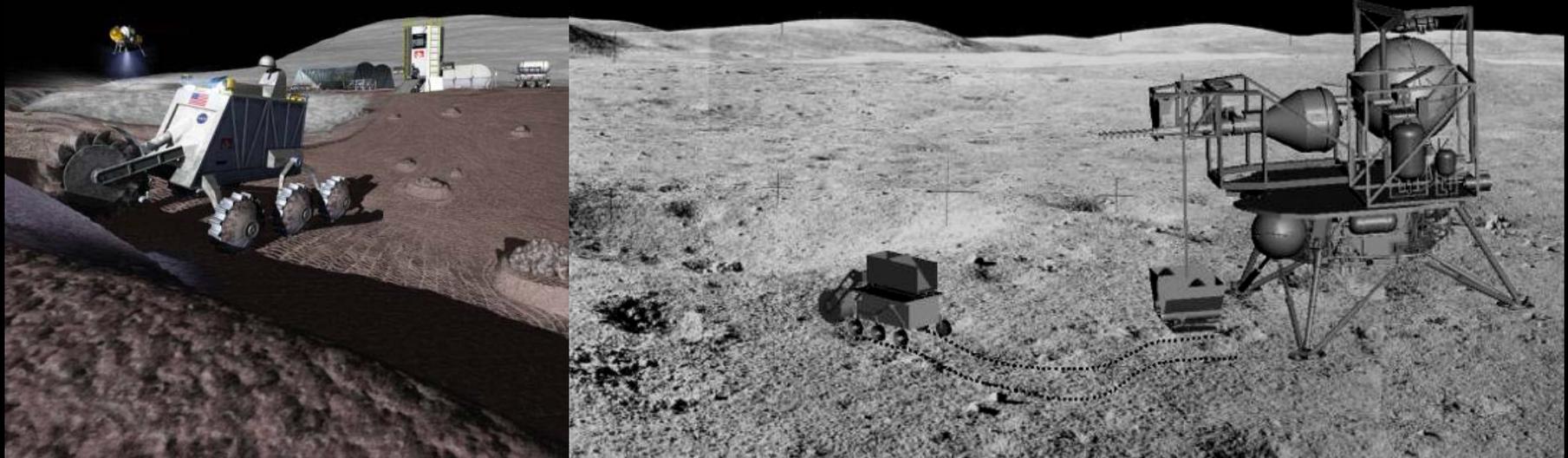
A second lunar analog test was performed in February 2010 at the same location on Mauna Kea in Hawaii. For this field test, the RESOLVE experiment was integrated onto a tandem-rover provided by the Canadian Space Agency (CSA), and a larger suite of science instruments were tested including: ground penetrating radar, cone penetrometer, Moessbauer/X-Ray Fluorescence, Multispectral Microscopic Imager (MMI), and the Volatile Analysis by Pyrolysis of Regolith (VAPoR) sample reactor and mass spectrometer. This second field test allowed for greater access to varied terrain and understanding of the effectiveness of instrument data on site and resource mapping.

A third lunar analog test between NASA and CSA that would continue and expand the interaction and integration of ISRU and science instruments is currently under consideration.

Using Analog Field Tests To Link and Prepare Science and In-Situ Resource Utilization for Future Space Missions



Presentation to European Planetary Science Congress
Rome, Italy, September, 2010





Presentation Overview



- Lunar and Mars science and In-Situ Resource Utilization (ISRU) resource assessment share common objectives
- Lunar and Mars science and ISRU resource assessment can share common instruments, hardware, field tests, and remote operations
- Lunar and Mars ISRU capabilities can enhance science mission return
- Further coordination between science and ISRU and SMD and ESMD is recommended



What is In-Situ Resource Utilization (ISRU)?

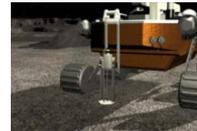


ISRU involves any hardware or operation that harnesses and utilizes 'in-situ' resources (natural & discarded) to create products and services for robotic and human exploration

Five Major Areas of ISRU

➤ Resource Characterization and Mapping

Physical, mineral/chemical, and volatile/water

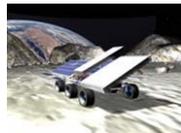
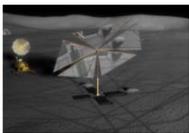
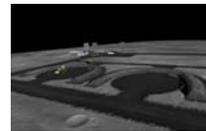


➤ Mission Consumable Production

Propellants, life support gases, fuel cell reactants, etc.

➤ Civil Engineering & Surface Construction

Radiation shields, landing pads, roads, habitats, etc.

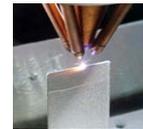


▪ In-Situ Energy Generation, Storage & Transfer

Solar, electrical, thermal, chemical

▪ In-Situ Manufacturing & Repair

Spare parts, wires, trusses, integrated structures, etc.



➤ **'ISRU' is a capability involving multiple technical discipline elements** (mobility, regolith manipulation, regolith processing, reagent processing, product storage & delivery, power, manufacturing, etc.)

➤ **'ISRU' does not exist on its own.** By definition it must connect and tie to multiple uses and systems to produce the desired capabilities and products.



Resource Assessment Synergism



Science

- Lunar Science
 - Physical and geologic composition, structure, origin, and evolution of the lunar crust and subsurface (mGEO-2, mGEO-5, and mGEO-10)
 - Location, distribution, and movement of solar, bombardment, and endogenous lunar volatiles (mGEO-9, mGEO-12, mGEO-13, and mGEO-14).
- Mars Science
 - “Follow the Water”

ISRU

- Lunar ISRU
 - Mineral distribution, especially iron-bearing, within 500 m of Outpost
 - Physical characterization; size & shape, rock, glass, and agglutinate content, bulk density, thermal capacity and conductivity, force required to penetrate/dig
 - Solar wind volatiles (H_2 , He, N_2 , CO)
 - Permanently shadowed crater resources, esp. hydrogen-bearing, and physical characteristics (H_2O , H_2 , NH_3 , CH_4)
 - Contaminants released during oxygen extraction processing (H_2S , HF, HCl)
- Mars ISRU
 - Water content, depth, and area distribution
 - Mineral & physical characteristics of water bearing materials
 - Contaminant release during water extraction



ISRU Can Enhance Science



Lunar Science

- Subsurface access with drill or excavation
 - Material brought to instrument
 - Down hole instrument placement or stratigraphy from trench
- Increased sample return capability
 - Increased sample mass with in-situ oxygen/fuel from Outpost for return
 - Hoppers from Outpost for sample collection (precursor to human hopper)
 - Increased propellant load (top-off tanks above nominal) for Altair ascent vehicle
- Decreased logistics from Earth with ISRU = Increased Science payload
- Science instrument alignment and placement with leveling/excavation capability

Mars Science

- Increased sample return capability
 - Increased sample mass with in-situ oxygen/fuel for return
 - Hoppers from Mars Outpost for sample collection (global reach)
- Gases for science instruments



Science and ISRU Share Common Instruments & Hardware



- **Science Instruments of common interest for ISRU Resource Characterization**
 - XRD/XRF – Mineral composition
 - Mossbauer Spectrometer – Iron-bearing minerals before & after processing
 - Raman Spectrometer/LIBS – Remote evaluation of minerals & water content
 - Gas Chromatograph (GC) – Molecular composition
 - Mass Spectrometer – Isotope composition
 - Neutron Spectrometer – water content/distribution
 - Ground Penetrating Radar – Subsurface features for excavation; ice layer

- **ISRU Resource Characterization hardware of possible interest to Science**
 - Integrated Optical/Raman – Particle size, shape imaging (Hand lens to 1 micron) & mineral composition
 - Core drill & sample transfer
 - Sample metering with self-cleaning window
 - Sample crusher w/ GC
 - Reusable volatile oven w/ GC – Pro is not sample number/size limited; Con is possible contamination for previous sample
 - Arm/scoop for subsurface access
 - 3-D terrain and mineral/resource mapping



What is an 'Analog' and Why Perform Analog Field Tests?



What is an 'Analog'?

- Facility or location that simulates one or more aspect of the exploration site
- Can range from fixed-based environmental chambers to natural or man-made earth-based terrain settings
- For ISRU, an analog field site needs to simulate terrain, minerals, and physical attributes of surface soils/regolith

Why Perform Analog Field Tests?

Concrete Benefits of Field/Analog Testing

- Mature Technology
- Evaluate Mission Architecture Concepts Under Applicable Conditions
- Evaluate Operations & Procedures
- Integrate and Test Hardware from Multiple Organizations
- Develop engineers and project managers

Intrinsic Benefits of Field/Analog Testing

- Develop International Partnerships
- Develop Teams and Trust Early
- Develop Data Exchange & Interactions with International Partners (ITAR)
- *Outreach and Public Education*



ISRU Analog Field Test Focus To Date



ISRU Objectives

1. Demonstrate mobile resource characterization (physical, mineral, and volatile) capabilities for lunar polar missions
2. Demonstrate technologies and end-to-end system operations for oxygen extraction from regolith
3. Demonstrate civil engineering and site preparation capabilities that might be required for future lunar human missions (landing pads, roads, protection, etc.)

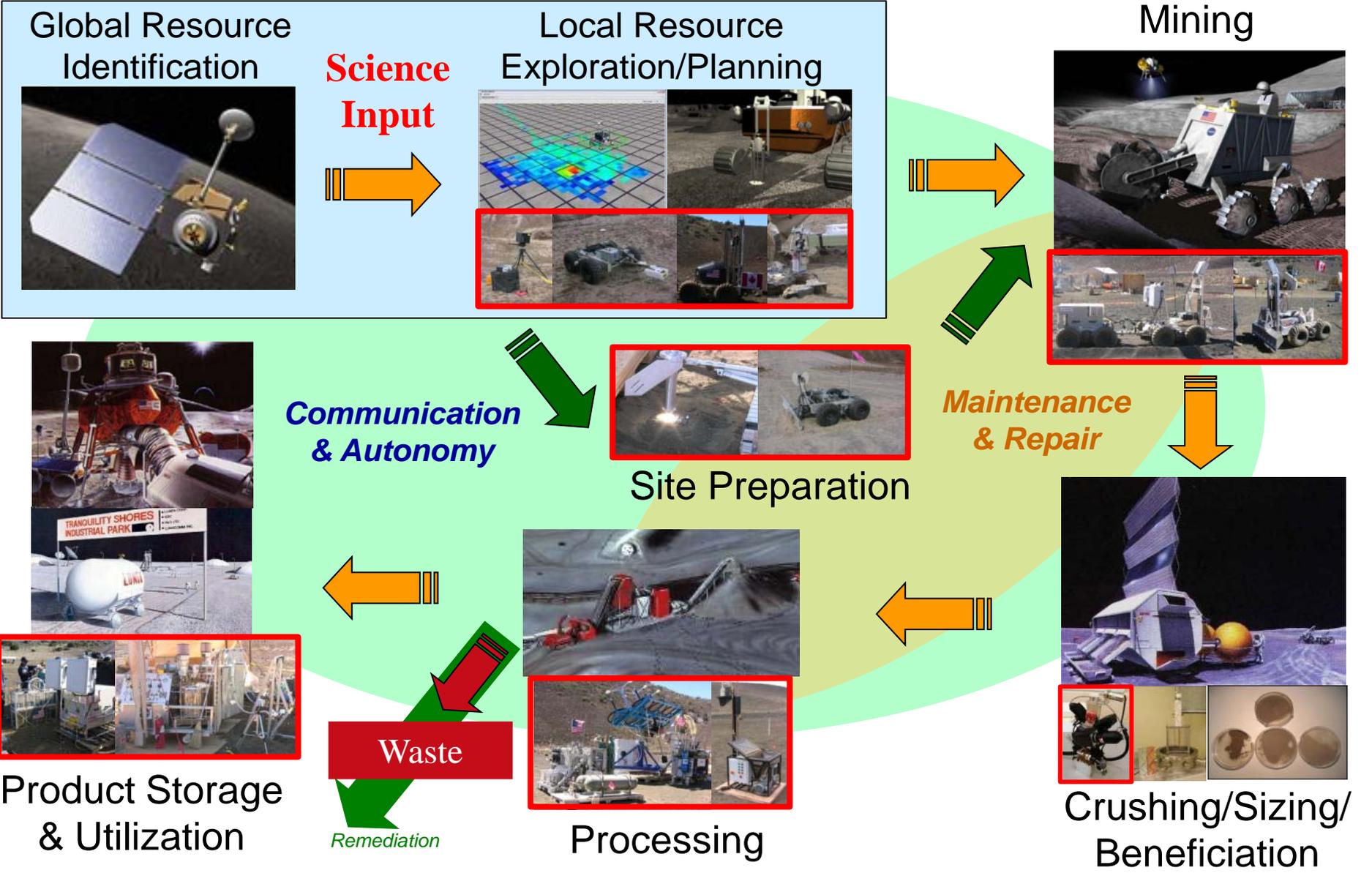
Interface and Interaction Objectives

- Link science operations and instrumentation with resource prospecting and mapping needs
- Link ISRU needs/products with Power, Propulsion, and Life Support consumable needs/waste
- Begin to assess interfaces and common hardware potential with Power, Propulsion, and Life Support system developers
- Coordinate ISRU development and system integration with International Space Agencies in mission critical roles



Analog Field Test Theme

Space ISRU 'Mining' Cycle





ISRU Analog and Field Test Site Requirements

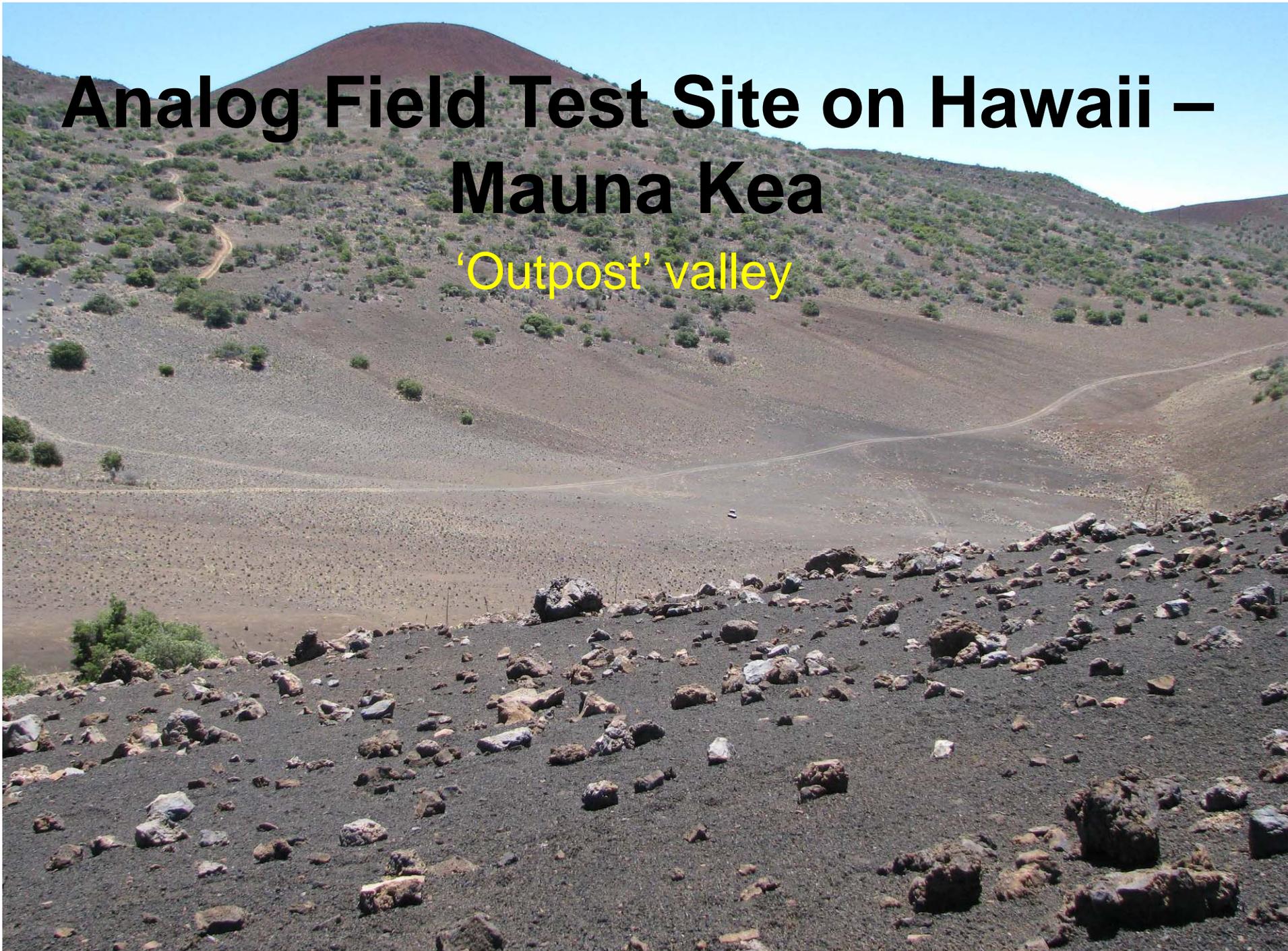


- Analog Must Have Similar Attributes to Site of Exploration Interest
 - Minimum vegetation (including ability to remove vegetation)
 - ‘Good’ Weather: Minimum rain and wind; Lots of sunlight; Reasonable temperatures (unless specifically needed for test objectives)
 - Open and relatively flat areas for ‘Outpost-like’ operations
 - Varied terrain and rock features for resource prospecting and science operations
 - Local material with similar physical characteristics to the Moon for excavation and site preparation
 - Local material with similar mineral characteristics to the Moon for resource prospecting, oxygen extraction, and processing
 - Local material that can be modified, processed, and permanently altered

- Analog Must Have Access & Infrastructure to Support Field Testing
 - Access
 - Reasonably close to airport for shipment of hardware; Ability to store hardware before personnel arrive
 - Access for all participants (government, industry, academia, and international space agencies)
 - Access and operations for ~14 days per test program; day and night if required
 - Security to control access of non-participants and secure hardware
 - Personnel Support
 - Lodging and food near test site for test personnel to minimize travel time and logistics
 - Personal hygiene facilities and refreshment/food capability at test sites
 - On-site medical support with rapid access to near-by hospital if required (< 1 hour)
 - Test Operation Support
 - Shelters & tents for personnel, in-site assembly/maintenance, and weather protection
 - On-site power (10’s of KW) and battery recharging capability
 - Gases and cryogenic fluids for test activities (oxygen, nitrogen, argon, helium, methane, etc.)
 - Access to assembly/maintenance facilities and local replacement materials (Home Depot)

Analog Field Test Site on Hawaii – Mauna Kea

'Outpost' valley



Craters with varied slopes & rocks



Lunar/Mars-Like Terrain & Soil





1st ISRU System Analog Field Test



Field Test Mission Objectives

▪ **Field Dates: Oct. 30 to Nov. 15, 2008** **Location: Mauna Kea , Hawaii**

▪ **Need for ISRU Field Test**

- Hardware from the ISRU Project needed to move from the laboratory to more challenging conditions
- ISRU Hardware had never operated in an end-to-end system before or had been field tested



▪ **NASA Hardware-Operation Objectives**

- 1. ISRU Mobile Resource Prospecting & Oxygen Production Demo Field Test:** Test resource prospecting, site survey, and oxygen production activities while integrated onto a mobile platform
- 2. ISRU End-to End Outpost Scale Oxygen Production & Storage Field Test (OPTIMA):** Demonstrated excavation, regolith delivery, regolith processing, and oxygen production and storage
- 3. Demonstrate partnership with State of Hawaii and Pacific International Space Center for Exploration Systems (PISCES):** Have PISCES 'host' field test activity by providing support, logistics, and facilities

5 NASA Centers, 2 International Space Agencies, 7 Companies, & 2 Universities



Lunar Prospecting & ISRU Demo (RESOLVE/Scarab) Field Test Tasks



- Demonstrate roving over multiple terrain features with complete RESOLVE-science payload
- Demonstrate dark navigation of Scarab over varied terrain and rock distribution
- Demonstrate drill site selection using TriDAR and Raman spectrometer via remote analysis at CSA PTOC
- Demonstrate remote operation of drill and sample transfer operations at CSA PTOC
- Demonstrate end-to-end operation of RESOLVE package
 - Min. of two times for resource prospecting: drilling, sample transfer, crushing, heating, volatile characterization; Max. 5 times
 - Min. of one time for oxygen extraction from regolith; Max. 3 times



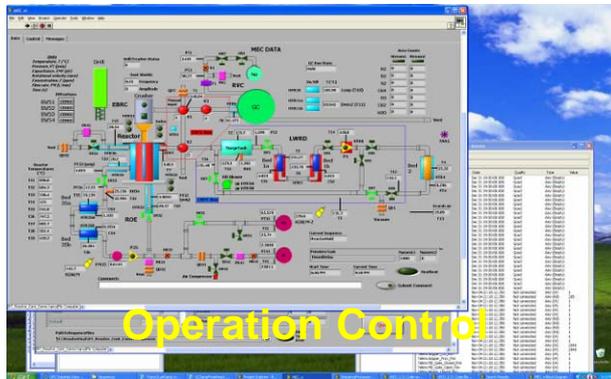
Installation



Material Transfer



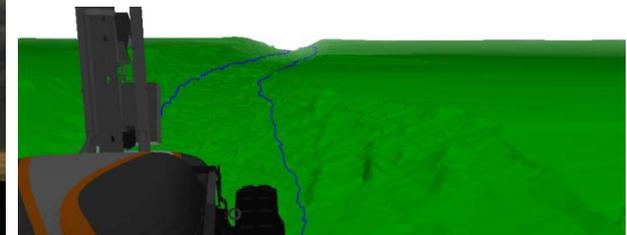
Drilling & Processing



Operation Control



Autonomous & Dark Navigation



Drill site approach navigation



Slope capability



Team



RESOLVE Field Test Accomplishments



- All software sequences tested successfully
- Performed 6 drilling operations
 - 4 to one meter depth
 - 1 into chilled > -37 C tephra (30 cm)
 - 1 into gray slope – aborted at ‘sandstone’ level (~3 inches below surface)
- The RESOLVE chemistry plant processed six RVC/LWRD cycles and four ROE cycles from four tephra corings.
 - Real-time measurements were acquired through autonomous control system
 - Regolith Volatiles Characterization (RV) experiment noted CO₂, H₂, O₂ and water during heating up to 150°C
 - Regolith Oxygen Extraction generated water, as expected, during one hour reduction process (~1 to 2% by mass)
 - Relative Humidity and capture beds were within 20% of Gas Chromatograph data (requirement for backup water measurement)
- Not one single electronics hardware failure associated with the chemistry plant occurred during the entire expedition.



Scarab Field Test Accomplishments



- Mobility tests completed in 5 terrain types (fine sand, medium sand 2.5/5.0/7.5 cm, pebbles): Tractive capability, Slope capability
- Long-distance nighttime (dark) navigation performed
 - Completed 2 overnight traverses over totaling over 26hrs and 3 km of autonomous driving
 - Increased terrain evaluation speed by factor of 4
 - Dust had no impact on TriDAR navigation
- 5 precision drill site approaches with TriDAR to down 1 mm from PTOC in Montreal
- Tweel wheel testing completed in 5 terrain types (400 kg Rover)
 - 20% less traction than rubber tire
 - 28% increase in traction with grouser
 - Slope 13.0° to 18.5° max. Lunar Wheel*
 - Slope 15.6° to 21.8° max. Rubber*
 - %50 Power differences between Lunar Wheel and Rubber Tire due to primarily sinkage (compaction resistance, Rc), 100W/160W
 - Rc Rubber Tire ~22% vehicle weight
 - Rc Lunar Wheel ~5% vehicle weight
- Lunar Wheel structure performed well
 - Dents did not propagate in glass fiber structure
 - Tear of PET spoke did not propagate



RESOLVE/Scarab Issues & Lessons Learned



Environment Lessons

- Sample core removal after 1 meter drilling in tephra different from laboratory testing – laboratory only allowed for 30 cm depth
 - Had to modify operations to overcome issue
- Temperature and humidity cycling pointed out weak points in the design
 - Cold solder joints
 - Cycling on wire connectors caused physical changes resulting in unexpected electrical failures
- Dust caused problems with drill electronics. Periodic cleaning required, Improvised with dust filter from local stores

Hardware Lessons

- Control software caused separate Drill – RESOLVE chemical plant coordination issues (rebooting and changing computers corrected problems)
- Sticky regulator in neon system ruptured burst disk. Correction made in field
- Data from Mossbauer helped evaluate ROE performance
- Multiple (equal) Partners required new integration understanding
 - Integration of RESOLVE onto Scarab effected by change in Scarab during shipping



Major Results From Nov. 2008 ISRU Analog Field Test



- ✓ Demonstrated end-to-end operation of mobile resource prospecting (RESOLVE/Scarab); roving over varied terrain, dark navigation, drill site selection; remote operation from CSA
- ✓ Demonstrated end-to-end oxygen extraction from regolith (PILOT & ROxygen) operations: regolith delivery, reactor fill/empty, regolith processing, water capture and clean-up, oxygen production
- ✓ RESOLVE: 6 Drilling, 6 Volatile characterization; and 4 Oxygen extraction operations
- ✓ PILOT: 6 complete reactor operations; 1000 ml of water produced from iron-oxide
- ✓ ROxygen: 5 complete reactor operations (2 Argon/3 Hydrogen)
- ✓ 1st Successful field deployment of ISRU
- ✓ Field deployment with International Partners, Canadian Space Agency and German Space Agency
- ✓ 1st field deployment where site access, test infrastructure, food, and lodging were provided by a 3rd party; Pacific International Space Center for Exploration Systems (PISCES)



2nd International Lunar Surface Operations (ILSO) - ISRU Field Test

Field Test Mission Objectives

- **Field Dates:** Jan. 24 - Feb. 14, 2010 **Location:** Mauna Kea , Hawaii
- **Field Test Purpose**
 - Advance ISRU hardware and system hardware over 1st analog field test; ISRU 'mining' cycle
 - Expand ISRU system/capability integration with other transportation and surface elements
 - Increase scope and criticality of international partner involvement in ISRU development
- **NASA Hardware-Operation Objectives**
 1. **O₂ Production from Regolith:** Test enhanced Oxygen extraction from regolith system & operations
 2. **ISRU Product Storage & Utilization:** Test hardware, operations, and energy systems that promote product usage
 3. **Lunar ISRU, Exploration, & Science Integration:** Integrate lunar exploration, resource & site evaluation, and lunar science objectives, instruments, and operations
 4. **Site Preparation:** Test hardware, operations, and surface sintering techniques
 5. **Field Geology Training:** Train astronauts, ISRU, and NASA/CSA management on geology

8 System Modules – 7 Instruments
6 NASA Centers, 6 Small Businesses, 5 Universities
(42 people plus visitors)

12 System Modules & Attachments; Infrastructure
3 Canadian Government Agencies, 8 Small Businesses, 2 Universities
(46 people plus visitors)



Hardware & Operation Integration at 2010 Field Test



Resource Characterization



Remote Ops & Satellite Communications



Load-Haul-Dump Rover



Solar Concentrator



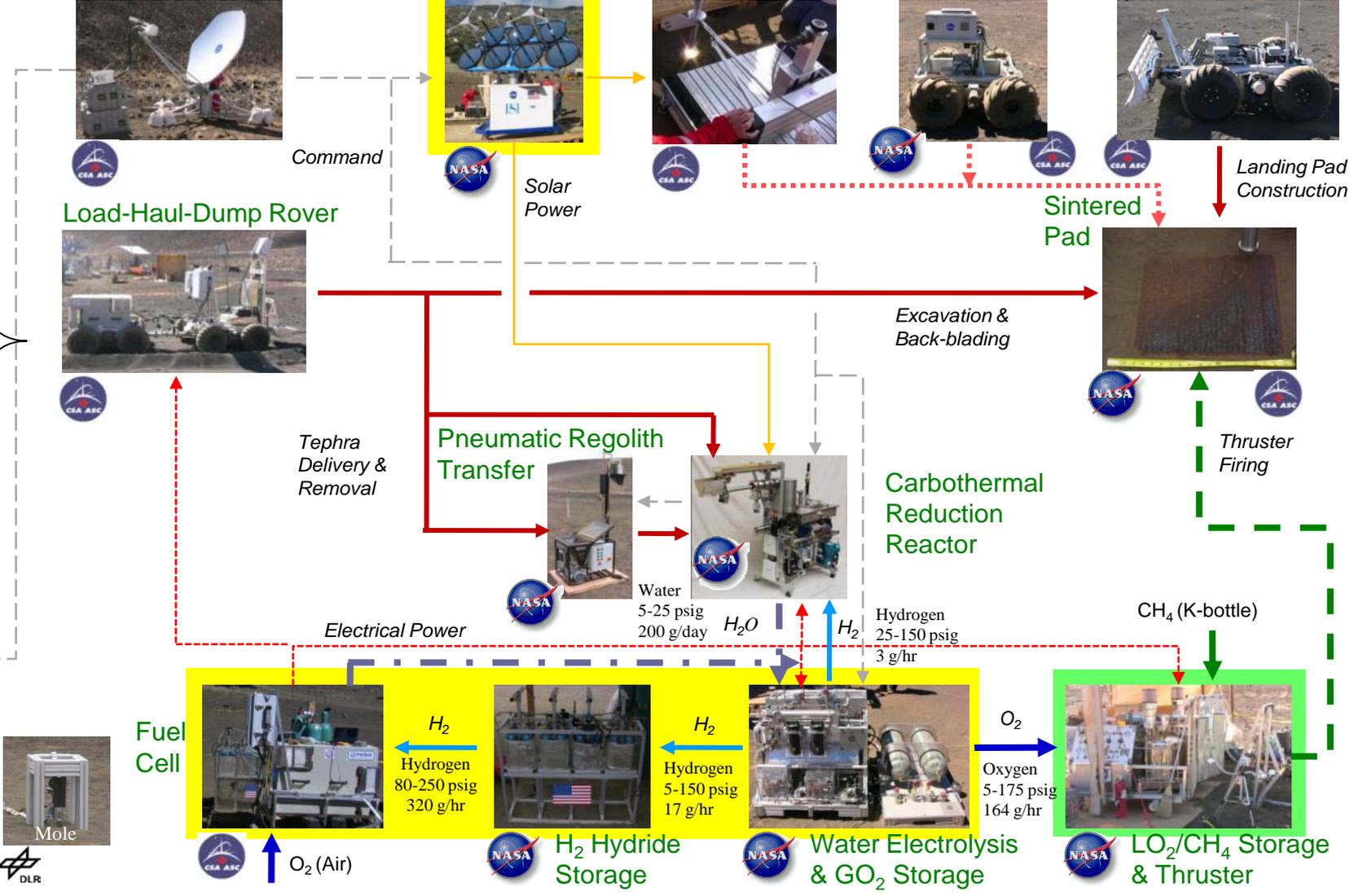
X-Y-Z Table



Resistive Sintering on Rover



3 DoF Blade on Rover





Obj. 3 – Integrate Lunar ISRU and Science Instruments



- **Test Objective:** Integrate lunar exploration, resource & site evaluation, and lunar science objectives, instruments, and operations
 - 3-A RESOLVE instrument package will be integrated on a CSA mobility platform to perform site characterization and site selection for excavation (**Joint NASA-CSA**)
 - 3-B Determine mineralization and volatiles present in core samples
 - 3-C Determine areas of enriched minerals appropriate for oxygen extraction
 - 3-D Utilize Mössbauer and Mössbauer/XRF instruments (1) to determine the iron-bearing minerals in core and surface samples for science exploration of the site and for prospecting for areas enriched in minerals for enhanced O2 production and (2) to analyze post processed tephra samples from the Carbothermal Reactor
 - 3-E Coordinate sample sites for ISRU, MMAMA/FSAT, CSA, and science instruments (**Joint NASA-CSA**)



RESOLVE on Tandem Unit



Crusher & Drill



Mossbauer/XRF on Rover



RESOLVED Reactor w/ Gas Chromatograph



Corner Cube Reflector on Pneumatic Stand



Thermal Heat-flow Probe



VAPoR Mass Spectrometer

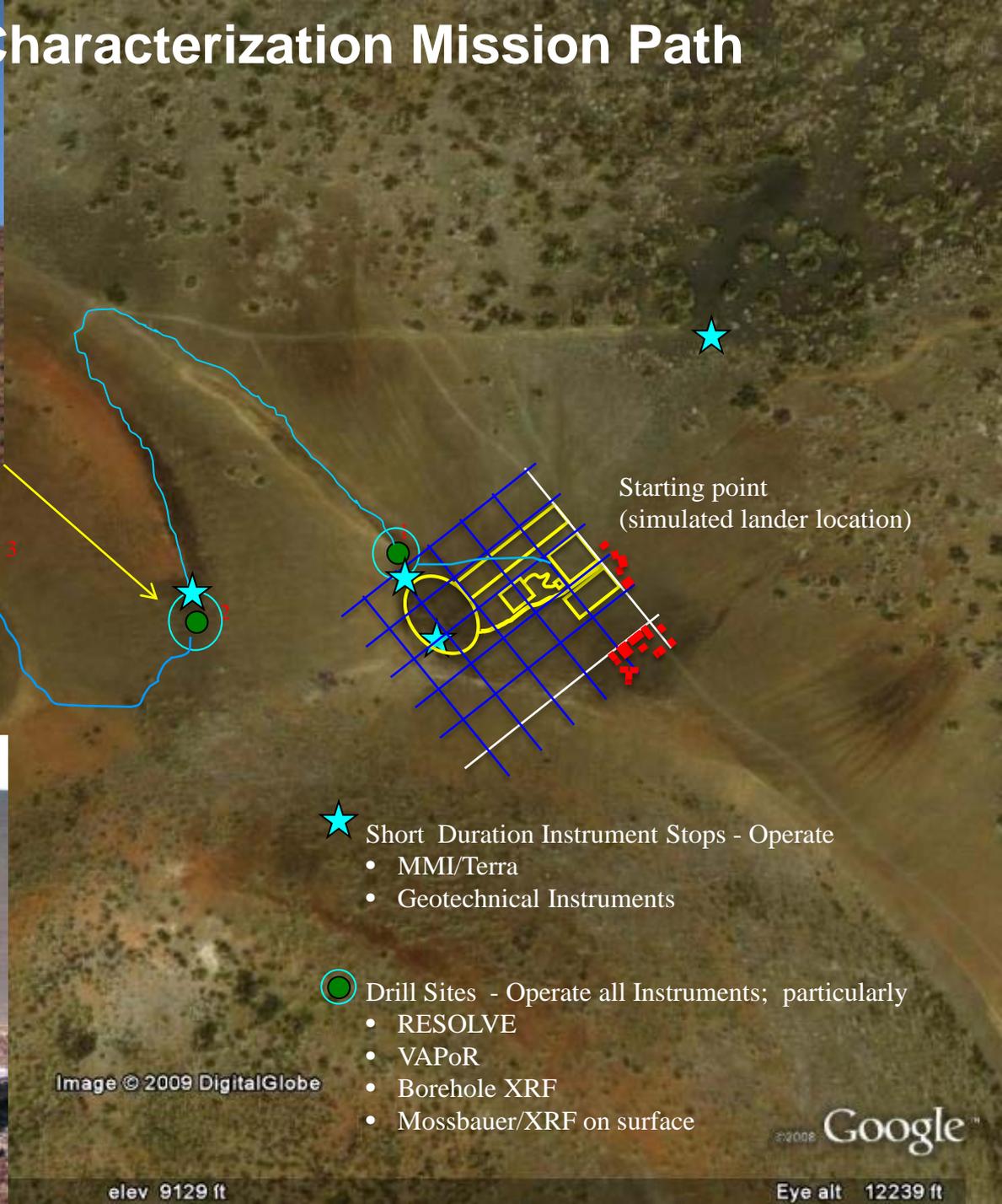


Multispectral Microscopic Imager (MMI)/Terra



Geotechnical & Sampling Tools

Polar Volatile Characterization Mission Path



Starting point
(simulated lander location)

- ★ Short Duration Instrument Stops - Operate
 - MMI/Terra
 - Geotechnical Instruments

- Drill Sites - Operate all Instruments; particularly
 - RESOLVE
 - VAPoR
 - Borehole XRF
 - Mossbauer/XRF on surface

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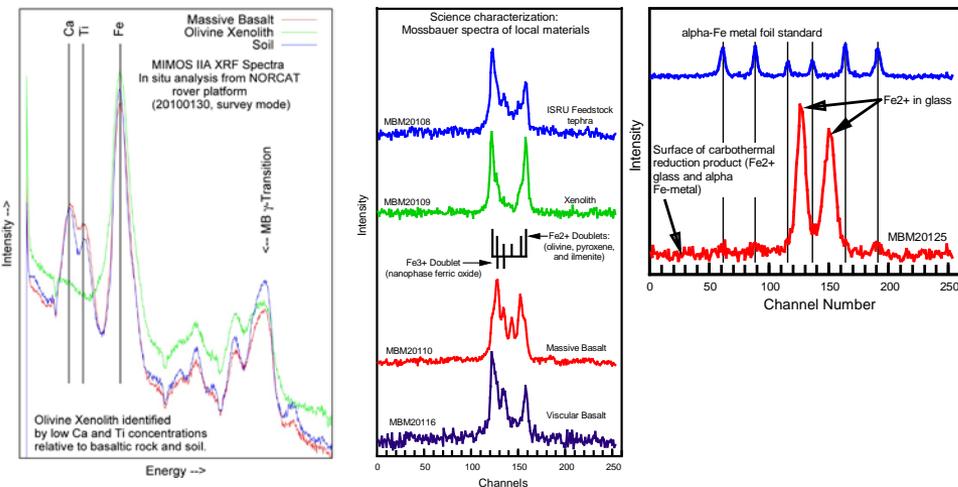
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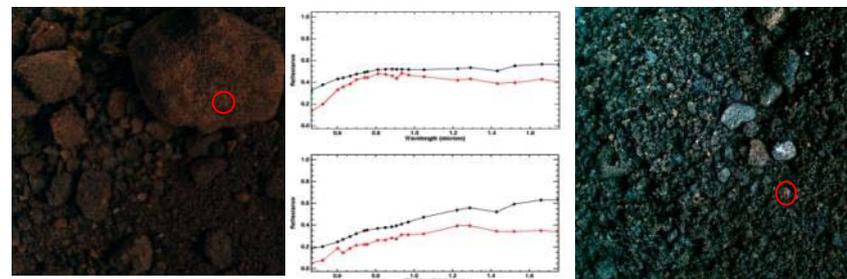
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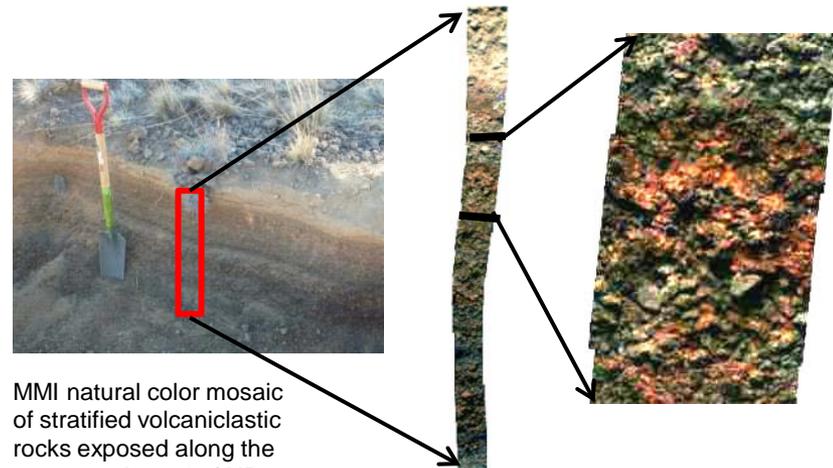
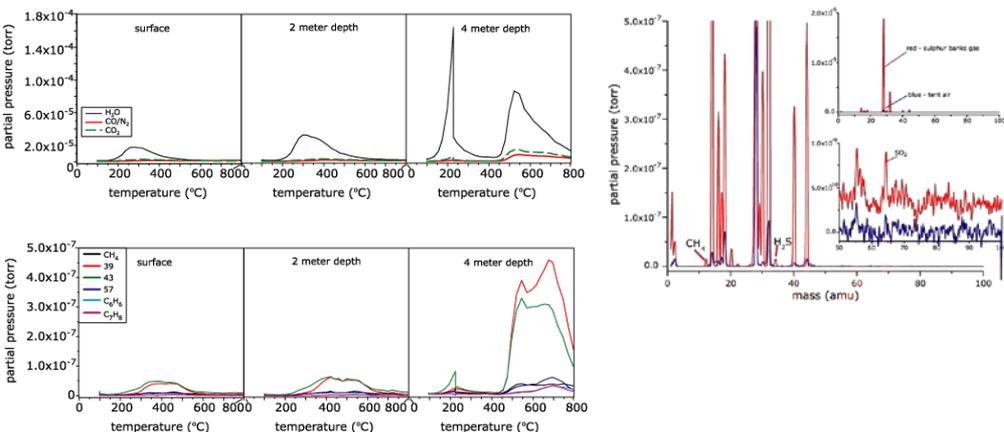
Mossbauer/XRF



MMI/Terra



VAPoR Preliminary Soil & Atm Results





Obj. 3 – Integrate Lunar ISRU Hardware and Science Instruments Results



- 3-A RESOLVE instrument package will be integrated on a CSA mobility platform to perform site characterization and site selection for excavation (**Joint NASA-CSA**)
 - Rover traverses to 4 drill locations: 1 in valley, 2 on crater rim, 3 & 4 in cinder crater
- 3-B Determine mineralization and volatiles present in core samples
 - RESOLVE processed 1 to 2 batches at each drill location measuring volatiles
 - VAPoR problems only allowed 9 samples to be processed (7 soil samples, 2 air samples)
- 3-C Determine areas of enriched minerals appropriate for oxygen extraction
- 3-D Utilize Mössbauer and Mössbauer/XRF instruments (1) to determine the iron-bearing minerals in core and surface samples for science exploration of the site and for prospecting for areas enriched in minerals for enhanced O₂ production and (2) to analyze post processed tephra samples from the Carbothermal Reactor
 - The calculated max O₂ yield based on the total Fe concentration (Fe²⁺ and Fe³⁺) in the feedstock tephra is ~3 gm O/(100gm Sample).
 - The calculated max O₂ yield based on the reduction of all metal oxides in the feedstock tephra except Al₂O₃ is ~37 gm O/(100gm Sample).
 - The calculated max O₂ yield based on the reduction of all metal oxides in the feedstock tephra is ~45 gm O/(100gm Sample).
- 3-E Coordinate sample sites for ISRU, MMAMA/FSAT, CSA, and science instruments (**Joint NASA-CSA**)
 - Samples collected at 4 RESOLVE drill sites
 - Samples collected from landing pad area, gray slope, and other areas of CSA-NASA interest



Obj. 5 – Field Geology & Astronaut Training



- **Test Objectives:** Train today's Astronauts, ISRU, and NASA/CSA management personnel in Geology using natural volcanic features on Hawaii
 - Not limited to just ISRU test site on Mauna Kea



↕ Lava flow near coast



'Apollo Valley' on Mauna Kea



Near Mauna Ulu



Thurston Lava Tube



Science Instrument & Operation Lessons Learned

- Need Science commitment early to maximize integration and instrument data usefulness; need single Point of Contact (POC) for field test with budgetary authority
- The science telecons prior to the activity were useful for arranging logistics and safety.
- Ad hoc collaborations between the various science experiments were productive. However, to maximize Science instrument deployment:
 - Set measurement objectives and identify science goals that involve collaborative measurements by multiple instruments in advance of field test
 - Conduct coordinated operational scenarios, and define a plan for collaborative science activities.
 - Perform advance planning for collaboration between the Science activities and ISRU activities.
 - Perform preliminary measurement integration and 3-D display on-site
- Time/day should be set aside in the middle of the field test to allow instrument PI/Teams to compare notes on findings and operation; present to each other
- Follow-up with post field test meeting of PI/Teams to compare results and lessons-learned with SMD & ISRU management



Major Results From 2010 ISRU Analog Field Test



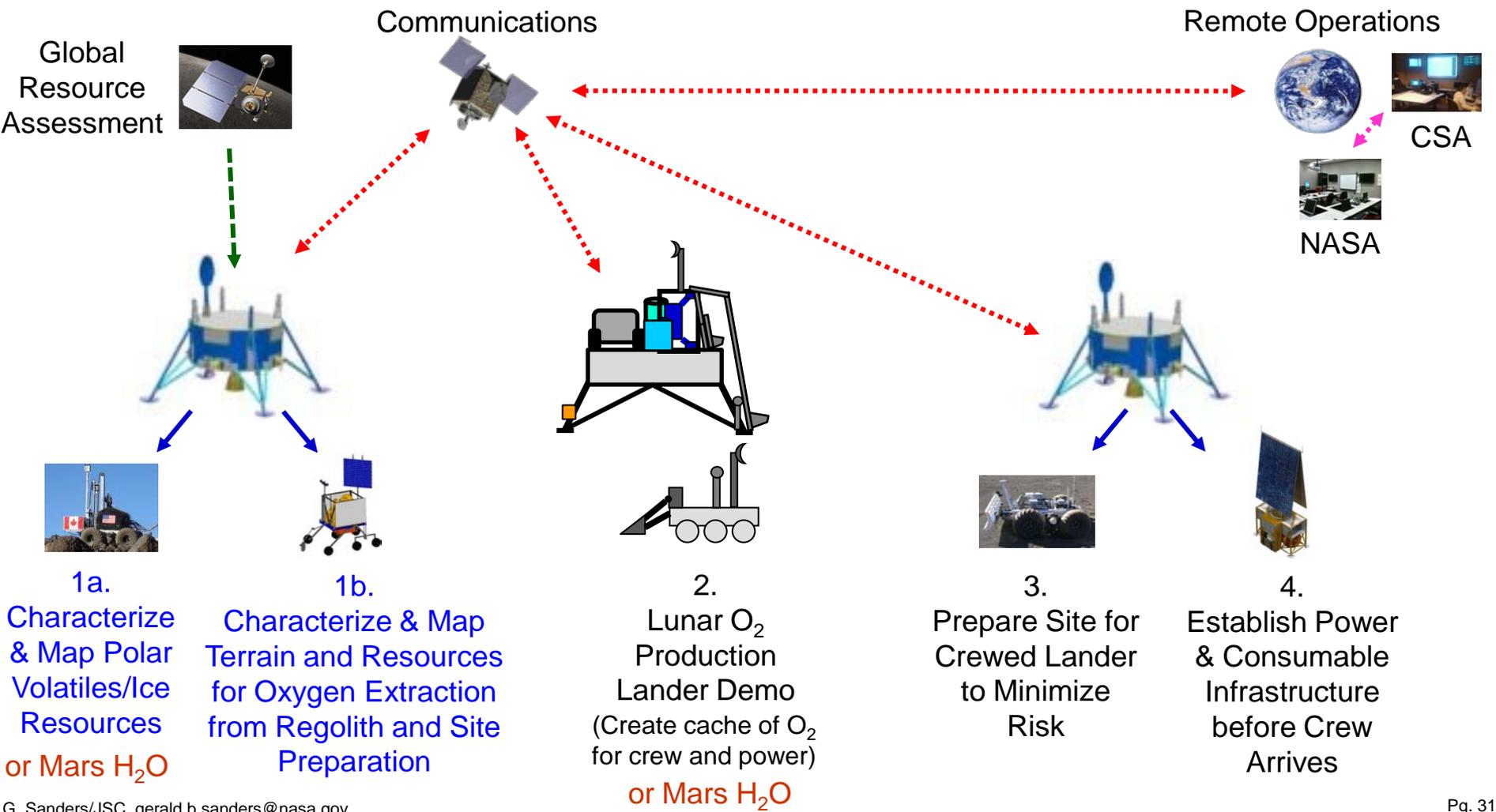
- ✓ Extracted oxygen from local tephra (28 gms or 9.6% ave. yield) using advanced processing and regolith transfer hardware in end-to-end configuration
- ✓ Electrolyzed water from tephra and fuel cell, transferred oxygen to cryogenic cart for liquefaction, and performed 17 LO_2/CH_4 thruster firings; “Dust to Thrust”
- ✓ Sintered two surface pads with two different methods and performed thruster firings with high speed camera to understand plume effects on unmodified and modified surfaces
- ✓ Integrated NASA and CSA/Canadian hardware in multiple critical applications
- ✓ Operated RESOLVE remotely from KSC and Solar Collector, Carbothermal Reactor, and Water Electrolysis systems remotely from JSC
- ✓ Tested SMD FSAT and MMAMA instruments for site/mineral characterization and support oxygen extraction process evaluation
- ✓ Completed field geology training with NASA and CSA managers and a CSA astronaut



Potential Areas of Interest for Future Analog Test



Scout & Prepare for Human Mission





Further Coordination Between Science and ISRU is Recommended and Required



- Develop common instruments or select instruments based on joint requirements
 - For both Moon and Mars

- Perform joint field demonstrations and Science Team activities
 - Select analog site that meets both Science and ISRU needs
 - Compare instruments utilized and measurements taken
 - Compare operations (ex. search pattern vs discrete sample selection)
 - Compare mapping and analysis procedures

- Evaluate joint robotic flight demonstration possibilities where hardware/capabilities are shared
 - What is in the permanently shadowed crater at the lunar poles?
 - What is the form and concentration of water near the surface on Mars?
 - Mars sample return with ISRU propellants as precursor for human missions