RESOLVE for Lunar Polar Ice/Volatile Characterization Mission

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Abstract

Ever since data from the neutron spectrometer instrument on the Lunar Prospector mission indicated the possibility of significant concentrations of hydrogen at the lunar poles, speculation on the form and concentration of the hydrogen has been debated. The recent impact of the Lunar Crater Observation and Sensing Satellite (LCROSS) along with thermal, topographic, neutron spectrometry, and radar frequency data obtained from the Lunar Reconnaissance Orbiter (LRO) have provided more information suggesting significant amounts of water/ice and other volatiles may be available in the top 1 to 2 meters of regolith at the lunar poles. The next step in understanding what resources are available at the lunar poles is to perform a mission to obtain ‘ground truth’ data. To meet this need, the US National Aeronautics and Space Administration (NASA) along with the Canadian Space Agency (CSA) have been working on a prototype payload known as the Regolith & Environment Science and Oxygen & Lunar Volatile Extraction experiment, or RESOLVE.

1. Introduction

The presence of large concentrations of accessible hydrogen and/or water at the lunar poles could have profound implications on the design and affordability of initial and long-term human Lunar and solar system exploration architectures. In particular, the ability to make propellants, life support consumables, and fuel cell reagents can significantly reduce mission cost by reducing launch mass by eliminating the delivery of consumables from Earth and enabling transportation system reusability; lowering risk by reducing dependence on Earth; and enabling extended surface operations and science by providing an energy rich environment and affordable access to multiple surface targets. The purpose of the RESOLVE experiment is to address fundamental science and resource questions such as “What resources are available on the Moon, where are they, and in what form?” as well as critical engineering questions, such as “How will we mine these resources, what extraction process is the most practical and efficient, and what are the engineering challenges to be faced in this environment?” The environment in the permanently shadowed regions at the poles is especially challenging due to the extremely low temperature (<40 K) and the unknown physical properties and content of trapped gases in the regolith and ice (if present). Two generations of RESOLVE have been built and tested and the 2nd generation of RESOLVE was field tested twice in Hawaii on the slope of Mauna Kea. The RESOLVE experiment is now in the 3rd generation of design which is aimed at both a mission simulation field test in June of 2012 and lunar environment simulation (vacuum) testing in 2014.

2. RESOLVE Overview

The RESOLVE experiment is a payload that can be mounted on a lander or preferably a rover. It consists of the following subsystems: 1) sample site selection subsystem (neutron spectrometer and near infra-red spectrometer), 2) sample acquisition and transfer subsystem (1 meter core drill and core transfer device), 3) sample processing subsystem (reusable sample heating oven), and 4) volatile characterization and water capture subsystem (gas chromatograph/mass spectrometer with water capture device). The RESOLVE experiment also includes its own structure, avionics, power conditioning and management, and thermal management subsystems, but requires power and communications from a lander or rover.

The mission of primary interest for lunar ice/volatile characterization will consist of a lunar rover and RESOLVE payload that is capable of mapping the horizontal distribution of hydrogen bearing volatiles,
and be capable of taking subsurface ground samples at a depth of up to one meter for analysis. The one meter core will then be divided into 8 segments to be heated up to 900°C with released gases analyzed for water and other volatiles that may be present. After all volatiles have been released, hydrogen would then be added to the sample to remove oxygen via the hydrogen reduction reaction. The mission would last ~5 to 7 days and perform 3 to 5 sample collection and processing operations in an area of several square kilometers.

3. Previous RESOLVE Designs [1, 2]

The RESOLVE experiment project started in 2005 through a NASA Internal Call for Proposals. The 1st generation of RESOLVE was aimed at subsystem design feasibility. Subsystem hardware for all process steps were built and independently tested. For the 1st generation of RESOLVE, separate reactors were designed and built for evolving lunar volatiles and extracting oxygen from regolith via the hydrogen reduction method. For volatile characterization, a COTS Siemens gas chromatograph was modified to meet mission measurement requirements and both hydrogen and water adsorption capacitance beds were incorporated as redundant measurement methods. A core drill with sample capture device for the complete 1 meter sample length was designed and built by NORCAT under contract to NASA with support from CSA.

In 2007, the 2nd generation of RESOLVE was initiated with the aim at building a ‘flight-like’ experiment package. Packaging and mass reduction efforts for the major subsystems were started, but work on minimizing avionics, power, and ground support equipment to operate in Earth’s atmosphere were not. A new combined volatile extraction/hydrogen reduction reactor was designed and built and both the sample collection drill and volatile characterization subsystems were modified from the 1st generation design. The 2nd generation RESOLVE was field tested for the first time in Nov. 2008 mounted on the ‘Scarab’ rover built by Carnegie Mellon University (CMU) under a NASA contract, and utilized a Neptec TrIDAR camera for nighttime navigation and drill site selection, under a CSA contract.

After the success of the field test in 2008, a subsequent field test was planned and performed in 2010 at the same analog location on Hawaii aimed at examining terrain and remote mission operation aspects not evaluated in the first field test.

4. RESOLVE 3rd Generation

In June 2010, the design phase of the 3rd generation of RESOLVE was initiated. The aim of this generation is to design and build a complete RESOLVE experiment, including power and thermal management, avionics, and structure to flight mass and power requirements of <60 kg and <200 Watts average. Included in the next generation RESOLVE is the addition of a neutron spectrometer and near infra-red spectrometer for the new sample site selection subsystem. The 3rd generation design effort will be performed in two stages. Stage 1 is a design that can operate under field test conditions and evaluate all operations and procedures associated with a 5 to 7 day mission on the Moon operated from NASA and CSA centers with mission applicable communication capabilities. Stage 2 is to modify the design for full operation under lunar environment conditions including thermal and radiator capabilities.

At the time of submitting this abstract, the 3rd generation RESOLVE experiment has completed its Preliminary Design Review for Stage 1. Also planning between NASA, CSA, and the University of Hawaii Hilo have started for the 3rd International Hawaii analog field test planned for June 2012.

Acknowledgements

The authors would like to recognize the hard work and dedication of all the people at NASA, CSA, CMU, NORCAT, EVC, Neptec, and the University of Hawaii-Hilo involved in designing the 1st, 2nd, and 3rd generations of RESOLVE as well as those that planned and executed the two analog field tests in Hawaii.

References


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European Planetary Science Congress
Nantes, France
October 2011

G.B. Sanders, W.E. Larson, J.W. Quinn, A. Colaprete, & M. Picard
## What We Know About Volatiles On The Moon

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Core Derived Water</th>
<th>Water/Hydroxyl</th>
<th>Polar Volatiles</th>
<th>Polar Ice</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solar Wind</strong></td>
<td>Apollo samples</td>
<td>M3</td>
<td>LCROSS</td>
<td>Mini SAR/RF</td>
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<tr>
<td><strong>Concentration</strong></td>
<td>Hydrogen (50 to 150 ppm) Carbon (100 to 150 ppm) Helium (3 to 50 ppm)</td>
<td>0.1 to 0.3 wt % water in Apatite 0 to 50 ppm water in volcanic glass</td>
<td>0.1 to 1% water</td>
<td>3 to 10% Water equivalent Solar wind &amp; cometary Volatiles (CO, H₂, NH₃, organics)</td>
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<tr>
<td><strong>Location</strong></td>
<td>Regolith everywhere</td>
<td>Regolith; Apatite</td>
<td>Upper latitudes</td>
<td>Poles</td>
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<tr>
<td><strong>Environment</strong></td>
<td>Sunlit</td>
<td>Sunlit</td>
<td>Low sun angle</td>
<td>Low or no sunlight; Temperatures sustained at &lt;106 K</td>
</tr>
<tr>
<td><strong>Depth</strong></td>
<td>Top several meters; Gardened</td>
<td>Top 10's of meters</td>
<td>Top mm's of regolith</td>
<td>Below 10 to 20 cm of desiccated layer</td>
</tr>
<tr>
<td>Column Density (# m⁻²)</td>
<td>Relative to H₂O(g) (NIR spec only)</td>
<td>Concentration (%)</td>
<td>Long-term Vacuum Stability Temp (K)</td>
<td>Instrument</td>
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<tr>
<td>------------------------</td>
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<td>-------------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>CO</td>
<td>1.7e13±1.5e11</td>
<td>5.7</td>
<td>15</td>
<td>UV/Vis</td>
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<tr>
<td>H₂O(g)</td>
<td>5.1(1.4)E19</td>
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<tr>
<td>H₂</td>
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<td>Ca</td>
<td>3.3e12±1.3e10</td>
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<tr>
<td>Hg</td>
<td>5.0e11±2.9e8</td>
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<td>NH₃</td>
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<tr>
<td>Mg</td>
<td>1.3e12±5.3e9</td>
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<td>C₂H₄</td>
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<td>0.0312</td>
<td>0.17</td>
<td>NIR</td>
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<tr>
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<td>0.0217</td>
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<tr>
<td>CH₃OH</td>
<td>7.8(42)E17</td>
<td>0.0155</td>
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<tr>
<td>CH₄</td>
<td>3.3(3.0)E17</td>
<td>0.0065</td>
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<tr>
<td>OH</td>
<td>1.7(0.4)E16</td>
<td>0.0003</td>
<td>&gt;300 K if adsorbed</td>
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<td>H₂O (adsorb)</td>
<td>0.001-0.002</td>
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<tr>
<td>Na</td>
<td>1-2 kg</td>
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<td>197</td>
<td>UV/Vis</td>
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<td>NHCN</td>
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<td>NH</td>
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<tr>
<td>NH₂</td>
<td></td>
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<td>UV/Vis</td>
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Volatiles comprise possibly 15% (or more) of LCROSS impact site regolith

*Chart courtesy of Tony Colaprete
Given: There are potentially substantial hydrogen rich resources on the Moon…

Then: We must gain the necessary knowledge to guide future mission architectures to allow effective utilization of in-situ resources to their fullest extent and optimum benefit.

- **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**
  - Can we effectively separate and capture volatiles of interest?
  - Can we execute repeated processing cycles (reusable chamber seals, tolerance to thermal cycles)?

Send a prospector to the surface of the moon to obtain this knowledge first hand.

That prospector is **RESOLVE**
RESOLVE is an internationally developed payload (NASA and CSA) 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 (Neutron Spectrometer, Near-IR Spectrometer)
  - Extract core sample from selected sites (Drill Subsystem)
    - To a depth of 1m with minimal loss of volatiles
  - Heat multiple samples from each core to drive off volatiles for analysis (OVEN Subsystem)
    - 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 (LAVA Subsystem)
    - Quantify important volatiles: H₂, He, CO, CO₂, CH₄, H₂O, N₂, NH₃, H₂S, SO₂
    - 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 (OVEN Subsystem)
    - From 150 C to 900 C
  - Flow H₂ through regolith to extract oxygen in the form of water (OVEN Subsystem)
  - Capture, quantify, and display the water generated (LAVA Subsystem)
RESOLVE Mission Requirements and Objectives

- Operate for the duration of the destination site’s illumination (est. 4-7 Earth days)
- Landing site shall have direct line of sight communications with Earth (eliminates cost of relay-sat)
- Rover shall explore, map/prospect potential water sites, and collect samples at multiple locations within a square km of the Lander at a depth up to ~1 meter
- Examine/measure composition, state and distribution of polar volatiles
- Measure geotechnical forces associated with acquiring samples (engineering data for future missions)
- Mass and power approximately 60 kg and 200W average power

<table>
<thead>
<tr>
<th>Resource Characterization</th>
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<tbody>
<tr>
<td>1</td>
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<tr>
<th>In-Situ Resource Utilization Demo</th>
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<td>9</td>
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<td>10</td>
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<tr>
<td>11</td>
</tr>
</tbody>
</table>

Science - Resource Focused
Engineering - Processing Focused
RESOLVE Development Background

Engineering Breadboard Unit #1 (2008)
- Volatile Reactor
- Drill, Sample Metering Device, & Crusher

RESOLVE Integrated System
- O₂ Production Demo

Demonstrate Subsystem Performance

Engineering Breadboard Unit #2 (2010)
- Combined Sample Metering & Crusher Unit
- Integration onto Scarab

RESOLVE Integrated System #2
- Combined Volatile Reactor & O₂ Production Demo

Demonstrate Integration & Operations
RESOLVE 3rd Generation
(Precursor to Flight)

Two-Phase Development
- Develop miniaturized unit for field test in June 2012
- Develop lunar vacuum compatible unit for testing in 2014

Subsurface Sample Collection –
Core Drill [CSA]
- Complete core down to 1 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 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

Two-Phase Development
- Develop miniaturized unit for field test in June 2012
- Develop lunar vacuum compatible unit for testing in 2014
RESOLVE 3rd Generation Hardware & System

1 m Core Drill & Sample Metering [CSA]

Oxygen & Extraction Node (OVEN)

Avionics

Water Capture

Gas Chromatograph - Mass Spectrometer

Neutron Spectrometer

Near Infrared Spectrometer
## Key Mission Drivers

<table>
<thead>
<tr>
<th>Key Mission Design Drivers</th>
<th>Option</th>
<th>Description/Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Science Location</strong> (Resource of interest)</td>
<td>Sunlit</td>
<td>Solar wind volatiles &amp; M3 hydroxyls&lt;br&gt;Pro: Most simple mission, long-duration possible&lt;br&gt;Con: Lowest science value</td>
</tr>
<tr>
<td><strong>Short Duration Sunlit</strong></td>
<td>Ice/volatiles below desicated layer in thermally stable zone&lt;br&gt;Pro: Can design to operate in sunlight with chance for good science&lt;br&gt;Con: Short duration mission (&lt;7 days)</td>
<td></td>
</tr>
<tr>
<td><strong>Shadowed Near Sunlit</strong></td>
<td>Ice/volatiles near surface and depth (LCROSS crater)&lt;br&gt;Pro: Good science and ISRU resource value&lt;br&gt;Con: must design for extreme low temperature conditions</td>
<td></td>
</tr>
<tr>
<td>Permanently Shadowed</td>
<td>Ice/volatiles and potentially thick ice (Spudis craters)&lt;br&gt;Pro: Great science value&lt;br&gt;Con: Extreme low temperatures and nuclear required for longer missions</td>
<td></td>
</tr>
<tr>
<td><strong>Sample Acquisition</strong> (Science value)</td>
<td>Downhole Device</td>
<td>Pro: Simple and quick verification of ice/water&lt;br&gt;Con: Limited sample size and number of volatiles that can be characterized</td>
</tr>
<tr>
<td>Auger (Honeybee) w/ Volatile Chamber</td>
<td>Pro: Simple, lower mass, and material broken up for easy transport&lt;br&gt;Con: Volatiles and ice may be lost (test required)</td>
<td></td>
</tr>
<tr>
<td>Sample Core Drill (CSA) w/ Volatile Chamber</td>
<td>Pro: Volatiles/ice contained; most pristine sample; International Partner&lt;br&gt;Con: Most complex and massive</td>
<td></td>
</tr>
<tr>
<td><strong>Mission Approach</strong></td>
<td>Lander Only</td>
<td><strong>Lander Mounted</strong>&lt;br&gt;Pro: Lowest mass and simplist integration/mission operations&lt;br&gt;Con: Sample only below lander (contaminated); limited control on selecting location</td>
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<tr>
<td></td>
<td><strong>Hopper Mounted</strong>&lt;br&gt;Pro: Similar to Lander but more locations can be examined&lt;br&gt;Con: Limited number of samples (2 to 3); limited control on selecting location</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Power, Comm, &amp; Payload on Lander/ Sample Collection on Rover</strong>&lt;br&gt;Pro: Rover allows selection of sample locations; lowest mass rover option&lt;br&gt;Con: Rover must return to lander limiting distance; sample transfer more difficult</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Power &amp; Comm on Lander/ Sample Collection &amp; Payload on Rover</strong>&lt;br&gt;Pro: Rover allows selection of sample locations; Simpler sample transfer&lt;br&gt;Con: Rover must return to lander limiting distance</td>
<td></td>
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<tr>
<td></td>
<td><strong>Rover Only</strong>&lt;br&gt;<strong>Solar or Battery Powered Rover</strong>&lt;br&gt;Pro: Rover has wide latitude to find best samples; simple mission ops concept&lt;br&gt;Con: Mission duration based on getting back to sun for recharging</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Nuclear Powered Rover</strong>&lt;br&gt;Pro: Rover has greatest latitude to find best samples&lt;br&gt;Con: Most complex and massive mission concept</td>
<td></td>
</tr>
</tbody>
</table>

*Bold Blue* denotes current mission driver option selected<br>*Red Italic* denotes backup option under consideration
RESOLVE Mission Options
Potential South Pole Landing Sites (1)

Maximum Days of Sunlight Using LOLA DEM
RESOLVE Mission Options
Potential South Pole Landing Sites (2)

Depth to Stable Ice (m)
RESOLVE Mission Options
Potential South Pole Landing Sites (3)

Neutron Depletion
RESOLVE Mission Options
Potential South Pole Landing Sites (4)

Slopes at 250 m Scale (deg)
RESOLVE Mission Options
Potential South Pole Landing Sites (5)

Net DTE Visibility Over Month (days): 2015-6-4
RESOLVE Mission Options
Potential South Pole Landing Sites (Summary)

Combined Site Analysis

<table>
<thead>
<tr>
<th>Site:</th>
<th>A</th>
<th>B</th>
<th>C</th>
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<tbody>
<tr>
<td>Shallow “Frost Line”</td>
<td>&lt;0.1 m</td>
<td>&lt;0.2 m</td>
<td>&lt;0.1 m</td>
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<tr>
<td>Slopes</td>
<td>&lt;10</td>
<td>&lt;15</td>
<td>&lt;10</td>
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<tr>
<td>Neutron Depletion</td>
<td>4.5 cps</td>
<td>4.7 cps</td>
<td>4.9 cps</td>
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<tr>
<td>Temporary Sun*</td>
<td>4 days</td>
<td>2-4 days</td>
<td>5-7 d</td>
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<tr>
<td>Comm Line of Sight*</td>
<td>8 days</td>
<td>17 days</td>
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* may not coincide
RESOLVE Mission Option – Site A

Cabeus Example (Site A)

~10 km

LCROSS Impact Site

LRO LROC WAC mosaic
RESOLVE Mission Options
Mission Architecture Qualitative Comparison of Scenarios

<table>
<thead>
<tr>
<th>FIGURE OF MERIT</th>
<th>LOCATION</th>
<th>Hopper</th>
<th>Crawl &amp; Die</th>
<th>Sun-Loving Rover</th>
<th>Sun &amp; Shadow Rover</th>
<th>X-Prize Lander &amp; Rover</th>
<th>Radioisotope Rover</th>
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<tbody>
<tr>
<td>LOCATION</td>
<td>PSR</td>
<td>PSR, Regional</td>
<td>PSR</td>
<td>Sunlit</td>
<td>Sunlit w/ brief shadow</td>
<td>Sunlit</td>
<td>PSR, Regional</td>
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<td>SCIENCE RETURN</td>
<td>PSR, 1 Bore, No Horiz Surveys</td>
<td>Regional Exploration</td>
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<td>Shallow Drill</td>
<td>Regional Exploration, Extended Mission</td>
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<td>2 DDT&amp;E</td>
<td>2 DDT&amp;E</td>
<td>2 DDT&amp;E, Industry Cost-Sharing</td>
<td>2 DDT&amp;E, Nuclear, Extended Ops</td>
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“Sun & Shadow” Rover Selected as Point-of-Departure for next Analysis Phase
RESOLVE Mission Notional Traverse

2 kilometers

100-m radius landing ellipse

- Major waypoint
- Discovery: traverse re-plan
- Excavation site
- Pre-planned traverse path
- Executed path

---

RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

---

Rove / Scan

Hot Spot Rove Seq

Rove / Scan

Hot Spot Rove Seq

Augur with NIR

Core 1 meter

Process Samples

---
**RESOLVE Status**

**Field Development Unit (FDU)**
- System Requirements Review: 1/28/11  *Completed*
- Preliminary Design Review: 5/25/11  *Completed*
- Critical Design Review: 7/26/11  *Completed*
- Subsystem delivery for integration: 2/6/12
- Integration and checkout complete: 3/23/12
- Integrated testing on rover complete: 4/20/12
- Field test: 6/12

**Vacuum Development Unit (VDU)**
- System Requirements Review: 7/27/12
- Preliminary Design Review: 11/30/12
- Critical Design Review: 7/26/13
- Integration and checkout complete: 3/28/14
- Vacuum chamber testing under lunar conditions: 7/30/14

*Partnership opportunities for VDU still possible*
QUESTIONS?