RESOLVE
Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

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Authors
Gerald Sanders, Landon Moore, David McKay, & Tom Simon/JSC
Ken Johnson, Greg Mungas, & Mike Pelletier/JPL
Dale Lueck & Clyde Parrish/KSC, Kurt Sacksteder/GRC
Mike Duke/CSM, Jeff Taylor/Univ of Hawaii, Larry Taylor/Univ. of Tenn.
Dale Boucher/NORCAT
Presentation Content

- Background/Rationale for RESOLVE
- What is RESOLVE?
- Teaming & Partnerships
- Original Design & Performance Characteristics for RESOLVE
- Progress to Date
- Wrap-up
Rationale/Background for RESOLVE
Rationale for RESOLVE

- The Clementine and Lunar Prospector orbital missions detected concentrations of hydrogen in permanently shadowed regions, but the form and concentration are not known.

- Oxygen makes up ~45% by mass of the lunar regolith (Apollo), and several processes to extract the oxygen can be used all across the lunar surface.

- In-Situ Resource Utilization (ISRU) to produce mission critical consumables, make spare parts, construct radiation shields and habitats, etc. can have a substantial impact on the mass, cost, and risk of individual missions and architectures for the Moon and Mars.
  - Oxygen production is important for life support, EVA, and propulsion (>75% of propellant mass is oxygen for O₂/methane and O₂/hydrogen systems).
  - Water extraction would eliminate need to bring rocket fuel and astronaut consumable water from Earth.
  - Manipulation and processing of lunar regolith is beneficial for dust mitigation, radiation shielding, & construction, but lunar regolith is highly abrasive and excavation and processing may be difficult.

- RESOLVE will develop technologies and processes that are critical to designing all subsequent regolith ISRU processing plants (equator and at poles).
  - Water and volatile (esp. hydrogen) extraction (applicable to both Moon and Mars).
  - Oxygen production from regolith and from electrolysis of extracted water.
  - Regolith and excavation characterization.

- RESOLVE is the first step in regolith ISRU development for the Moon and Mars.
What We Know About Water on the Moon So Far

1994: Clementine
Bi-static Radar Indicates Possible Water Deposits In Lunar South Pole

1998: Lunar Prospector
Neutron Spectrometer Indicates Elevated Levels Of Hydrogen Near Lunar Poles

1999: Lunar Prospector
Controlled Crash Into Lunar Surface. No Water Indicated, However Considered Inconclusive.

2003: Arecibo
(Earth-based Radar) Data Indicates No Thick Ice Deposits In Polar Craters

Laser Altimeter
High Resolution Camera
Neutron Detector (5 km resolution)
Surface Temperature Detector
Galactic Cosmic Ray Effects
Mini-RF
RESOLVE provides critical data and experience for subsequent ISRU missions to the Moon and Mars

**Resource Assessment**
- Remote & Local Sensors
- Simulants

**In-Situ Resource Excavation & Separation**
- Regolith Excavation
- Thermal/Microwave Extraction
- H₂O Separation
- CO₂ & N₂ Separation

**Resource Processing**
- Regolith Reduction for O₂ & Feedstock
- CO₂ Reduction
- H₂O Reduction
- Fuel Production
- Bio-Support Production

**Consumable Storage & Distribution**
- Cryocoolers
- Light Weight Tanks
- Disconnects/pumps

**RESOLVE**

- Provides Water & Gases For Power, Propulsion, Life Support & Science
  - Lunar Polar Water Explorer
  - Prospector Flt. Exp. (Missions of opportunity)
  - Lunar Volatile & He³ Extraction
  - Mars Polar Water Extraction Demo

- Provides O₂ & Reactants Power, Propulsion, Life Support & Science
  - Lunar O₂ Production Demo
  - Lunar O₂ Pilot Plant
  - [H₂O]
  - Mars O₂ & Fuel Production Demo
  - Mars ISPP Sample Return

**RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction**
What is RESOLVE?
What is RESOLVE?

Program Description

- Project initiated through ESMD ICP last June under the Technology Maturation Program (official project start 2/1/05)

- Divided into two phases:
  - Phase 1 (Year 1; $3.6M): Develop conceptual design and perform breadboard concept verification testing of each of the experiment modules
  - Phase 2 (Years 2-4; $20.4M): Develop flight prototype unit and test in relevant environment

Task Description:

- The RESOLVE Project will develop and fabricate a prototype device that will excavate lunar regolith from permanently shadowed craters, determine the quantity and form of hydrogen in and the physical/mineralogical characteristics of the regolith, and demonstrate ISRU.

- RESOLVE team members will utilize relevant design experience, technology development, and hardware from laboratory investigations and past flight experiment projects
  - Mars In-situ propellant production Precursor (MIP) flight experiment
  - Microcopy, Electrochemistry, & Conductive Analyzer (MECA) flight experiment
  - Regolith Evolved Gas Analyzer (REGA)
  - Camera, Hand Lens and Microscopic Probe (CHAMP)
  - Mars Microbeam Raman Spectrometer (MMRS)
  - Mars drill
What Will RESOLVE Do?

- Confirm the signatures sensed by Lunar Prospector are in fact due to hydrogen.
- Determine the form and concentration of this hydrogen.
- Demonstrate a chemical process to extract oxygen from regolith.
- Determine physical characteristics of the polar regolith to provide geologic context and soil mechanics properties.
- Demonstrate the capture of water and/or hydrogen evolved from the regolith. Split the water into hydrogen and oxygen.
- Provide critical information to facilitate architecture and mission planning for future human missions.
## RESOLVE Objectives

### Resource Characterization

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<tr>
<td>1</td>
<td>Determine form and concentration of hydrogen in permanently shadowed regions</td>
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<tr>
<td>2</td>
<td>Determine other volatiles available</td>
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<tr>
<td>3</td>
<td>Determine grain size distribution and morphology of regolith</td>
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<td>4</td>
<td>Determine quantity of which volatile(s) are evolved by excavation &amp; crushing</td>
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<td>5</td>
<td>Determine chemical/mineralogical properties</td>
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<td>6</td>
<td>Determine bulk excavation related physical properties of regolith</td>
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<td>7</td>
<td>Demonstrate capture and separation of water</td>
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<td>8</td>
<td>Demonstrate oxygen extraction</td>
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<td>9</td>
<td>Engage &amp; Excite Public/Education Outreach</td>
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### In-Situ Resource Utilization Demo

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<tr>
<td>1</td>
<td>Determine difference between sunlit and shadowed regions</td>
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<td>2</td>
<td>Determine spatial distribution of resources</td>
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<td>3</td>
<td>Demonstrate scalable extraction/processing techniques</td>
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<tr>
<td>4</td>
<td>Demonstrate scalable oxygen production technique</td>
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Additional experiment goals if payload & mission design allow.

Rover required

Science - Resource Focused

Engineering - Processing Focused

Rover required
RESOLVE Overview

The five RESOLVE modules are:
- **EBRC - Excavation and Bulk Regolith Characterization (KSC/CSM/NORCAT)**
  Provide capability of extracting samples of regolith from the lunar surface and determine bulk characteristics of the regolith.
- **ERPC - Environment and Regolith Physical Characterization (JPL)**
  Determine the fine-grain and chemical characteristics of regolith samples and the regolith temperature in the permanently shadowed crater.
- **RVC - Regolith Volatile Characterization (KSC/GRC)**
  Provide capability of evolving and measuring volatiles from regolith samples to determine the form and concentration of hydrogen bearing molecules in shadowed regions near the lunar poles.
- **LWRD – Lunar Water Resource Demonstration (KSC)**
  Demonstrate the ability to capture and quantify water and hydrogen produced/evolved by the ROE and/or RVC from the regolith samples. In addition the LWRD shall split the water that is captured into hydrogen and oxygen using electrolysis.
- **ROE - Regolith Oxygen Extraction (JSC/Boeing/CSM/ORBITEC)**
  Demonstrate the ability to chemically extract oxygen from the regolith samples.

• **RESOLVE will incorporate five experiment modules from three NASA institutions; JSC, KSC, JPL (with involvement from GRC & MSFC)**
• **JSC will integrate the modules into engineering & flight-like prototype units**
• **Significant Industry & University Involvement**
• **RESOLVE is currently in conceptual design phase of project**

**RESOLVE Target Design**
- Mission Design Life = 7 days in shadowed crater
- Mass = 30 kg
- Average Power; 100 Watts
Integrated Schematic & Flow Diagram

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

Drill → Thermal Envelope → Sample Extracted (Core Tube, Scoop on Arm)

Sample Extracted → Sample Pretreated (Crusher, Sieve)

Physical Characterization (Optical Microscope, Raman Spectrometer)

Sample Pretreated → Oxygen Extracted (Heating Chamber, Reactant Control)

Gases Identified and Quantified (GC, Mass Spec)

Volatiles Evolved (Sealed Heating Chamber, Fluidizer)

Water Captured (Anhydrous Salts, Adsorption Beds, Membranes, Freezing)

Hydrogen Captured (Anhydrous Salts, Adsorption Beds, Membranes, Freezing)

Hydrogen Electrolyzed → Hydrogen Storage

Water Electrolyzed → Water Storage

Oxygen Extracted → Oxygen Storage

Processed Regolith → Mixed Gases

Spent Regolith

Spent Regolith → Waste Gases

To Lunar Vacuum

Combined RVC and Hydrogen Reduction ROE Heating Chamber

Gerald. B Sanders/JSC, gerald.b.sanders@nasa.gov
How is RESOLVE Organized?

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

Principle Investigator, Jerry Sanders
Project Manager, Landon Moore

Science Advisory Team (SAT)
Lead Scientist, Dave McKay

System Engineering And Experiment Integration Team (SEEIT)
Chief Engineer, Bernie Rosenbaum

Education and Outreach Team
Lead, Mike O’Neill

Experiment Modules

Core Elements

Excavation and Bulk Regolith Characterization
(Drilling/Crushing)

Environment and Regolith Physical Characterization
(Microscope/Mineralogy/Temperature)

Regolith Volatile Characterization
(Evolve Volatiles and Quantify)

Regolith Oxygen Extraction
(Extract Oxygen from Regolith)

Lunar Water Resource Demonstration
(Capture Water/Hydrogen and Electrolyze)

Master Controller

Thermal Control

Structures and Mechanisms

Instrumentation

Electrical Power Distribution and Control
Teaming & Partnerships
RESOLVE Team

Johnson Space Center (JSC)
- Provides project and system engineering/integration management and control
- Leads Science Advisory Team
- Provides expertise on regolith processing to extract oxygen
  - Co-I for Regolith Oxygen Extraction experiment module.
  - Developer of one of the Regolith Oxygen Extraction methods – Hydrogen reduction

Jet Propulsion Laboratory (JPL)
- Provides expertise on scientific instrument options (ie. microscope and RAMAN spectrometer)
  - Co-I for Environment and Regolith Physical Characteristic experiment module
- Provides expertise on mission design and lander/rover interface details
- Provides expertise on an instrument to measure the regolith temperature at depth

Kennedy Space Center (KSC)
- Provides expertise on regolith excavation
  - Co-I for Excavation & Regolith Bulk Characterization experiment module
- Provides expertise on regolith processing and gas analysis systems
  - Co-I for Regolith Volatile Characterization experiment module
- Provides expertise on water capture methods
  - Co-I for Lunar Water Resource Demonstration experiment module

Glenn Research Center (GRC)
- Provides expertise on reduced-gravity effects on particle fluidization and heating
  - Critical support for Co-I for Regolith Volatile Characterization experiment module for heating & regolith fluidization

Marshall Space Flight Center (MSFC)
- Provides expertise on regolith simulants to be used in testing
- Supports system engineering and integration
RESOLVE Team (Cont.)

Science Advisory Team
- Provides critical knowledge and guidance on instrument options and potential lunar polar environment and regolith properties
  - Dr. Dave McKay – JSC – Expert in Lunar regolith properties
  - Dr. G. Jeffrey Taylor - University of Hawaii - Petrologist/geochemist with decades of experience working on Apollo samples
  - Dr. Larry Taylor – University of Tennessee - Petrologist/geochemist directly involved with Apollo missions and sample analysis
  - Dr. Mike Duke – Colorado School of Mines - Geoscientist experienced in NASA planetary exploration programs and space resource development concepts.
  - Dave Carrier – Lunar Geotechnical Institute - Veteran Apollo Lunar geotechnical engineer

Colorado School of Mines (CSM)
- CSM provides expertise on terrestrial and space excavation & mining
- Developer of one of the Regolith Oxygen Extraction methods – Electronic reduction in molten salt

Northern Centre for Advance Technology (NORCAT) & EVC
- Provides hardware for Excavation & Bulk Characterization experiment module
- Canadian Space Agency (CSA) currently funding NORCAT/EVC for Mars drilling technology

Boeing
- Developer of one of the Regolith Oxygen Extraction methods – Molten electrolysis

Orbital Technology Corp (ORBITEC)
- Developer of one of the Regolith Oxygen Extraction methods – Carbo-thermal reduction
Original Design & Performance Characteristics for RESOLVE
RESOLVE Design Parameters

- LRO will have provided landing site information and will serve as data relay back to Earth

- RESOLVE will be a payload on a lander or rover
  - Host provides power, communications, and mobility (if rover)
  - RESOLVE is self contained (except for power & communications)
  - RESOLVE controls its own operations and stores data until host transmits.

- Neutron spectrometer (or other sensor) for resource reconnaissance is provided by rover

- Target mass and power: 30 kg and 100 W ave.

- Sample collection & preparation:
  - Core, 1 meter deep with volatile containment
  - 3 drilling operations minimum; 10 drilling operations nominal
  - Core transferred to processor in 4 segments (25 cm length - 1.5 cm diameter per segment)
  - Core sample crushing capability down to 1 mm (max.) before volatile release and oxygen production processing
  - Measure species and amount of trapped volatiles release during transfer and crushing

- Bulk and fine regolith characterization
  - Measure excavation parameters during sample collection: internal angle of friction, bearing strength, compaction, layering, and bulk density
  - Measure regolith fine physical properties: shape, size distribution, mineral/chemical characteristics
  - Camera and microscopic imaging that provides its own illumination
RESOLVE Design Parameters (Cont.)

- **Water/volatile processing**
  - Process 4 core segments (~50 ml compacted regolith) per sample collection operation
  - If water is present, capture 0.25 to 2 ml of water total (3 operations); water will be separated, condensed, and visually verified
  - Water will be electrolyzed after capture
  - Measure constituents (under 100 AMU) and amount of water & volatiles released

- **Oxygen production from regolith**
  - Produce minimum of 5 grams of oxygen with 80 watts power maximum per production cycle
  - Perform a minimum of 2 production cycles to validate sealing and feedstock/spent regolith transfer; 5 production cycles nominal
  - Mass <10 kg; Volume < 15 liters
  - Minimize heat loss and production cycle time
  - Design a demonstration package with plans for how the process can be scaled up

- **If rover is available, perform following evaluations at 3 locations minimum; 10 locations nominal**
  - Core sample collection
  - Bulk & fine regolith characterization
  - Hydrogen/water (H$_2$/H$_2$O) and evolved volatile processing
Progress to Date
Issues Addressed by Science Team

- Ice sublimation rate at extremely low temperatures and pressures
- Probability of hitting rock given a known drill bit diameter
- Permanently shadowed lunar regolith property estimation
  - Bulk JSC-1/ice mixture (at LN₂ temperature) characterization testing performed to provide range of expected hardness/compactness
  - ORBITEC JSC-1/ice mixture hardness characterization
- Trace element identification for sensor and processing hardware poisoning concerns
- Polar regolith subsurface temperature profile
- Likelihood of volatile loss due to regolith heating from drilling
- Lunar polar simulant definition and production to allow testing of each experiment module
  - Simulant material for polar regolith physical and mineralogical requirements has been located by NORCAT & University of New Brunswick and
  - Processing has begun (crushing and melting) to obtain desired mineral, rock, and breccia fragments, glasses, and agglutinates
  - Nano-phase iron particle simulant definition at Univ. of Tennessee has begun
  - New simulant can be mixed with JSC-1 to tailor physical and mineralogical characteristics
Progress to Date

**EBRC (Excavation/Drilling/Crushing)**

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- Sample extraction (1 meter drill)
  - Preliminary drill bit design depth/force testing complete
  - Custom drill bit and auger designed; in fabrication
  - Core capture device for sample designed; prototype complete
- Sample transfer and preparation
  - Sample transfer and segmenting device designed; in fabrication
  - Roll crusher designed; in fabrication

Previously developed drilling system
Will serve as platform for RESOLVE Phase 1 drill/auger testing

Images provided by NORCAT
Progress to Date

ERPC (Physical/Mineral/Temperature Characteristics)

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

- **Design Origin**
  - The optical imaging/microscopy system design based on Camera, Hand Lens and Microscopic Probe (CHAMP)
  - The Raman Sectrometer follows the design of the Mars Microbeam Raman Spectrometer (MMRS)
  - ERPC combines elements of MMRS & CHAMP into single instrument capable of operating on the Moon
  - ERPC Soil Probe follows the design of the Soil Probe for Netlander

- **Accomplishments**
  - Identified imaging microscope and RAMAN spectrometer as best candidates for RESOLVE
  - Verified through testing that single set of optics can be utilized for both instruments
  - Completed preliminary design/layout with following capabilities:
    - Far-field imaging with long integration times available for monochromatic imaging in crater
    - Hand lens imagery mode at 30 microns/pixel and microscopy mode at 3 micron/pixel resolution allowing >90% of total soil particle distribution
    - Continuous variable distance/magnification imagery
    - >1.5 mm Field of View in microscopy mode
    - Color imaging and fluorescence at hand-lens to microscopic mode with red, green, blue, white, and UV light LED illumination
    - Regolith mineral content to within 1 wt% per compound
    - Measure regolith temperature to <1 K accuracy
Progress to Date

RVC (Volatile Evolution and Quantification)

- **Sample Heating Oven/Chamber**
  - Resistive & microwave heating concepts under evaluation
    - Simulant with nano-phase iron under development
  - Various oven configurations built (transparent, cylindrical, 2D)
  - Initial testing of mechanical fluidization (ie vibration) complete
  - Modeling of particle interaction/mixing behavior initiated

- **Evolved Gas Identification/Quantification**
  - Trade between Gas Chromatograph (GC) and Mass Spectrometer (MS) performed to meet RESOLVE requirements; GC selected
    - Various column configurations traded
  - COTS MEMS-based Gas Chromatograph for Phase I investigation which meets 90% of RESOLVE measurement needs has been identified and is being procured
  - Carrier gas system designed and hardware under procurement

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**Laboratory Testing Concepts for the Regolith Volatile Characterization Oven**

- Cylindrical RVC Oven for Volatile Extraction
- 2D RVC Oven for Mixing/Heating Visualization
- Penetrations for resistance heater, thermocouples and evolved gas flow

**Details of Siemens MicroSAM GC**

- Analytical Modules
- Control Module
- Power & Communication
- Electronic Module
- Supply Gases & Vents

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Gerald. B Sanders/JSC, gerald.b.sanders@nasa.gov
Progress to Date
ROE (Oxygen Extraction)

- **ROE requirements:**
  - Produce minimum of 5 grams of oxygen with 80 watts power max. per production cycle
  - Perform a minimum of 2 production cycles to validate sealing and feedstock/spent regolith transfer; 5 production cycles nominal
  - Mass <10 kg; Volume < 15 liters

- **Accomplishments**
  - Contracts with three competing vendors in place
    - Orbital Technologies Corp. (ORBITEC): Carbo-thermal reduction
    - Colorado School of Mines (CSM): Electronic reduction in molten salt
    - Boeing: Magma electrolysis
  - Each vendor has begun bench-top proof-of-concept testing to support the RESOLVE demonstration requirements
  - JSC In-house design of hydrogen reduction system test bed complete; Testing to begin shortly
  - Each technology lead is developing a scaled up design to quantify the benefits of the technology if it were employed in a large scale production plant
  - Down-selection to a single concept by end of Oct.
Progress to Date
LWRD (Capture & Separation of Water/Hydrogen)

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- **Water Capture**
  - Survey of various hydrated salts (30) for the adsorb/desorb characteristics of water complete
  - Differential scanning calorimeter/thermal gravimetric analyzer (DSC/TGA) scans of dehydration of salts performed to examine:
    - Weight loss & energy as a function of temperature
    - %water released (capture capacity)
  - Down-selected to two for more detailed testing
  - Evaluation of thermal separation concept in work with testing immanent

- **Hydrogen Capture**
  - Survey of various metal hydrides (47) for the adsorb/desorb characteristics of hydrogen complete
  - Four selected for subsequent testing; testbed built and characterization testing has begun

- **Water Electrolyzer**
  - Alkaline-based water electrolyzer selected after trade (does not have to remain wet)
  - Two electrolyzers under procurement; one has been received and performance testing has started
  - Water electrolysis demonstrated when water is added to dried alkaline membrane.
Wrap-up
RESOLVE Summation

- **RESOLVE team is uniquely qualified to perform future lunar polar mission**
  - Leading ISRU experts within NASA at JSC, KSC, JPL, GRC, & MSFC
    - Corporate knowledge gained for future ISRU missions
  - Leading experts on Lunar regolith properties, minerology, and environment
  - Leading experts on oxygen extraction from regolith within NASA and industry
  - World experts on planetary excavation and mining (CSM/NORCAT)
  - Partnership with Canadian Space Agency for hardware and funding possible

- **RESOLVE hardware uniquely designed to provide critical data and experience for subsequent ISRU missions to the Moon and Mars**
  - Significant progress has been achieved since start of the project (2/1/05)
  - Drill/core capture mechanism (NORCAT) minimizes volatile loss and maximizes knowledge of resource and bulk regolith properties
    - Applicable to Mars robotic precursor for water characterization
  - Optical/mineralogical instrument (JPL) provides both local/navigation imaging as well as fine grain and chemical characterization of the regolith
  - Hydrogen, water, and oxygen extraction processes provide early data and expertise for subsequent efforts
  - Design can be modified to meet RLEP 2 mission requirements (within reason) and can incorporate new features if required (i.e. neutron spectrometer)