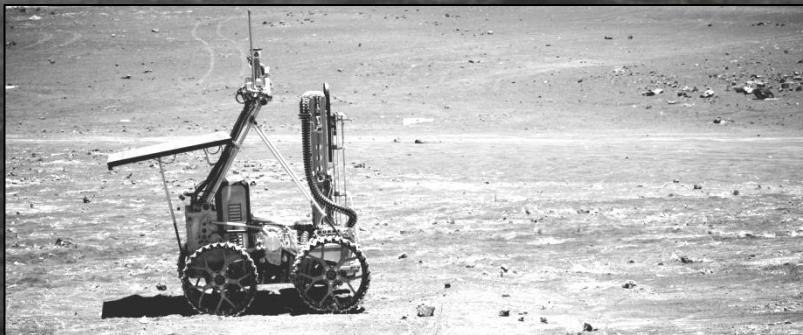


# **RESOLVE**

## **LUNAR ICE/VOLATILE PAYLOAD DEVELOPMENT AND FIELD TEST STATUS**

Presentation to LEAG  
Oct. 24, 2012



### **NASA**

KSC  
JSC  
GRC  
ARC  
JPL

### **CSA**

NORCAT  
Neptec/ODG  
Xiphos



**G. B. Sanders**, R.S. Baird, K. N. Rogers, NASA/JSC  
W. E. Larson, J. W. Quinn, J. T. Smith, NASA/KSC  
A. Colaprete, R. C. Elphic, NASA/ARC  
M. Picard, CSA



# Presentation Overview



- **RESOLVE Payload Development Status**
- **RESOLVE Polar Mission Analog Field Test & Results**



# RESOLVE PAYLOAD DEVELOPMENT STATUS



# What is RESOLVE?

Regolith & Environment Science and Oxygen & Lunar Volatile Extraction



**RESOLVE** is an internationally developed payload (NASA and CSA) that that can perform two important missions for Science and Human Exploration of the Moon

## Prospecting Mission: (Polar site)

### ✓ **Verify the existence of and characterize the constituents and distribution of water and other volatiles in lunar polar surface materials**

- Map the surface distribution of hydrogen rich materials
- Determine the mineral/chemical properties of polar regolith
- Measure bulk properties & extract core sample from selected sites
  - To a depth of 1m with minimal loss of volatiles
- Heat multiple samples from each core to drive off volatiles for analysis
  - From <100K to 423 K (150 C)
  - From 0 up to 100 psia (reliably seal in aggressively abrasive lunar environment)
- Determine the constituents and quantities of the volatiles extracted
  - Quantify important volatiles:  $H_2$ , He, CO,  $CO_2$ ,  $CH_4$ ,  $H_2O$ ,  $N_2$ ,  $NH_3$ ,  $H_2S$ ,  $SO_2$
  - Survive limited exposure to HF, HCl, and Hg

## ISRU Processing Demonstration Mission: (Equatorial and/or Polar Site)

### ✓ **Demonstrate the Hydrogen Reduction process to extract oxygen from lunar regolith**

- Heat sample to reaction temperature
  - From 423 K (150 C) to 1173 K (900 C)
- Flow  $H_2$  through regolith to extract oxygen in the form of water
- Capture, quantify, and display the water generated



# RESOLVE Development Toward Flight



Internal Call for Proposal Awarded 2006

Performed Lunar Polar Design Ref Mission



Lab. Tests

1<sup>st</sup> & 2<sup>nd</sup> ISRU  
Analog Test

3<sup>rd</sup> ISRU  
Analog Test

Lunar Env.  
Chamber Test

**Gen I**

2006-2007

*Demonstrate Feasibility & Subsystem Performance*

- Hardware designed to demonstrate functions needed for RESOLVE
- Minimal integration between functions
- Minimal software and autonomous control development
- No mission operation considerations
- Not considered in design:
  - Flight environment
  - Mass, power, and volume
  - Mission operations



**Gen II**

2007-2008

*Demonstrate Integration & Operations*

- Hardware designed to demonstrate functions needed for RESOLVE in one 'flight like' package
- Flight mass and volume for RESOLVE functions considered in design
- Start of software and control development
- Start of mission operation considerations
- Not considered in design:
  - Flight environment
  - Flight-like avionics and power conditioning, and ground support hardware



**Gen IIIA**

2010-2012

*Develop 'flight like' unit for mission simulation*

- Hardware designed to address lunar polar ice/volatile mission requirements
- Software and control development
- Focus on mission operations
- Design to operate under lab/analog conditions with path to lunar env.



**Gen IIIB**

2012-2014

*Develop flight prototype for vacuum operation*

- Hardware designed to operate under lunar conditions
- Focus on
  - Flight design for all RESOLVE hardware
  - Software & control of hardware operation
  - Mission operation timeline and power profile
  - Environment: vacuum, temperatures, EMI, materials





# RESOLVE Development Toward Flight



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  - Flight design for all RESOLVE hardware
  - Software & control of hardware operation
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  - Environment: vacuum, temperatures, EMI, materials





# RESOLVE Analog Field Tests



**Nov. 2008**

- RESOLVE Gen II on Scarab Rover
- Power, avionics, and ground support equipment on separate trailer



**FEB. 2010**

- RESOLVE Gen II+ on CSA Juno Rover
- Power, avionics, and ground support equipment on separate Juno



**July 2012**

- RESOLVE Gen IIIA on CSA Artemis Jr. Rover
- Everything on single rover platform

**Purpose: Develop a flight-like unit that can fit on a rover and operate in the lunar environment**

## Sample Acquisition System

### Auger/Core Drill Subsystem [CSA]

- Collect and transfer subsurface material down to 1 m below surface
- Maintain sample stratigraphy and volatiles (below 150 K)
- Meter samples for processing
- Auger material to surface for evaluation
- Measure geotechnical properties of regolith during drilling

## Surface Mineral/Volatile Evaluation

### Near Infrared Volatile Spectrometer Subsystem (NIRVSS) - ARC

- Measure surface bound OH/H<sub>2</sub>O while traversing (at min. of 0.5% by mass)
- Detect form of water (ice/hydration) in auger tailings
- Detect water vapor in evolved gases
- Image surface and drill tailings

## Resource Localization

### Neutron Spectrometer Subsystem (NSS) -ARC

- Locate hydrogen and hydrogen bearing volatiles down to 1 meter below the surface while traversing (at min. of 0.5% by mass)

## Volatile Content/Oxygen Extraction

### Oxygen & Volatile Extraction Node (OVEN) - JSC

- Accept samples from Sample Acquisition System
- Heat samples from <150 K to 423K for volatile extraction
- Heat samples to 1173 K for oxygen extraction
- Transfer evolved gases to LAVA volatile analyzer

## Volatile Content Evaluation

### Lunar Advanced Volatile Analysis (LAVA) - KSC

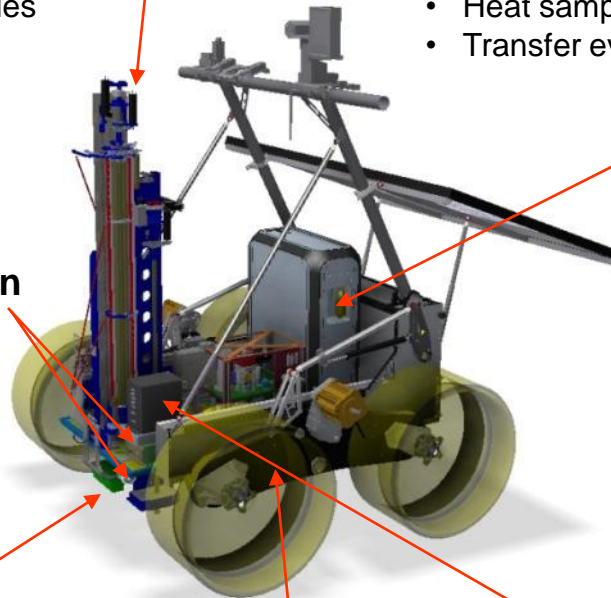
- Accept evolved gas from OVEN; provide hydrogen for oxygen extraction
- Perform analysis in under 2 minutes
- Measure water content in evolved gas
- Characterize volatiles of interest (below 70 amu)
- Measure D/H and O<sup>16/18</sup> isotopes
- Capture & image water evolved

## Operation Control Flight Avionics - KSC

- Space-rated microprocessor
- Control subsystems and manage data

## Surface Mobility [CSA]

- Traverse wide range of lunar surface/material conditions
- Tele-operation and autonomous traverse modes
- Carry RESOLVE payload; provide power, comm., and thermal management

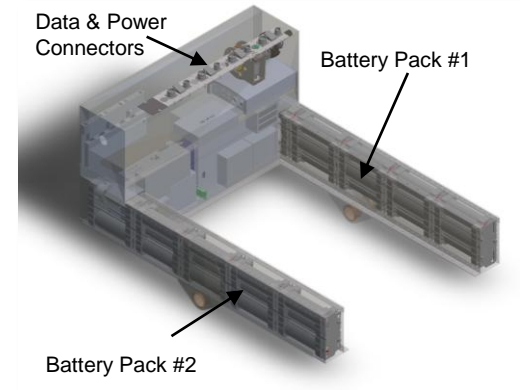
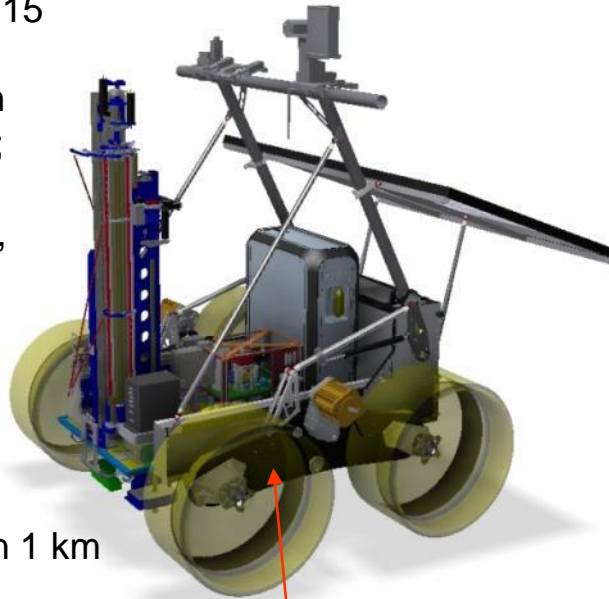




**Purpose: Develop a flight-like unit that can fit on a rover and operate in the lunar environment**

## Gen IIIA: Field Development Unit)

- Mass <230 kg w/o payload (Goal 170 kg)
- Travel 3 km
- Ascend/descend slopes of at least 15 (Earth gravity)
- Ground clearance of at least 25 cm
- Maintain nom. speed of 10 cm/sec; max. 3 km/hr (83 cm/s)
- Carry RESOLVE payload; <125 kg, 0.684 m x 1.00 m
- Provide 300 W ave.; 400 W peak to RESOLVE (5 kW\*hr battery) and communications
- Tele-operation and autonomous drive modes
- Absolute Localization of 1 m (within 1 km range)
- Path Re-Trace Accuracy of 10 cm (after 2 m traverse past point)
- Position accuracy of **x** and position hold capability while drilling



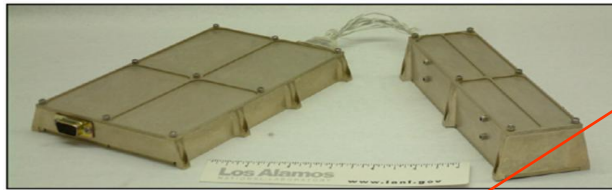
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- Tele-operation and autonomous traverse modes
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## Gen IIIA: Field Development Unit

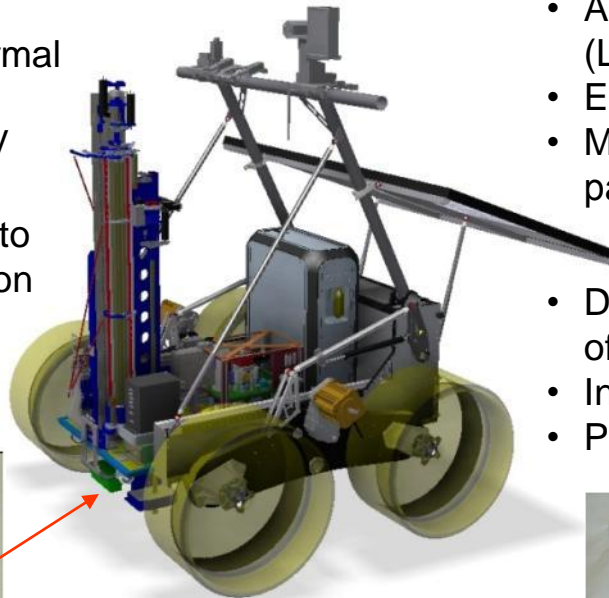
- Existing 'Hydra' unit built by Los Alamos
- Mass: 480 gm + 100 gm for source),
- Power: 1.8 W
- Measure both Thermal and Epithermal neutrons
- Energy range: <0.01 eV to 500 keV
- Area efficiency 13 cm<sup>2</sup>
- Requires neutron source (Cf 252) to operate – Limits depth of penetration and field of view for detection



## **Resource Localization**

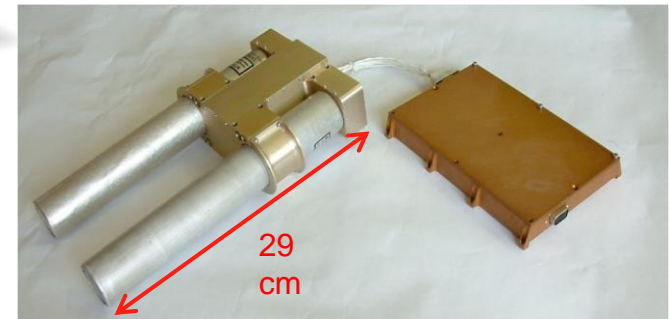
### **Neutron Spectrometer Subsystem (NSS) -ARC**

- Locate hydrogen and hydrogen bearing volatiles down to 1 meter below the surface while traversing (at min. of 0.5% by mass)



## Gen IIIB: Engineering Test Unit

- Measure both Thermal and Epithermal neutrons
- Area efficiency of at least 64 cm<sup>2</sup> @ 1eV (LEND = 35 cm<sup>2</sup>)
- Energy range from 0.03 eV to 1 MeV
- Map to 1 meter depth and ~ 1 m wide path at rover speed ≤10 +/- 1 cm/s
- Detect water at a minimum abundance of 0.5% by mass with <10% uncertainty
- Instrument Mass: 1.85 kg
- Power: 2 W ave.; <4 W max for heaters



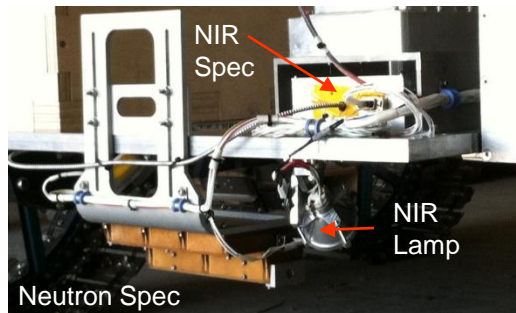
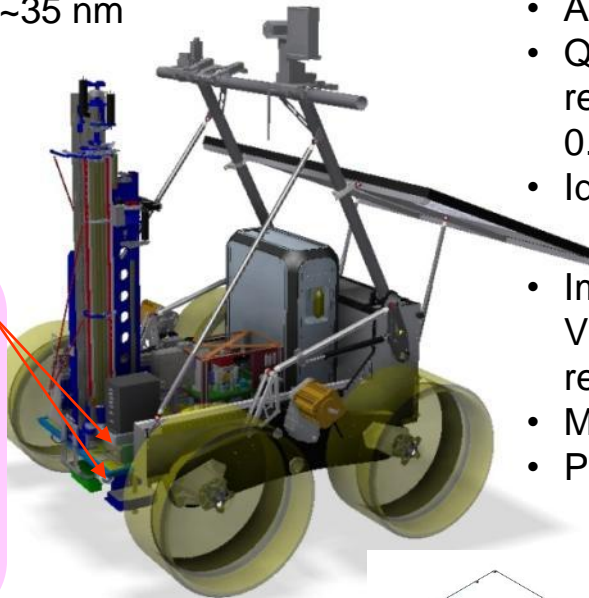
**Purpose: Develop a flight-like unit that can fit on a rover and operate in the lunar environment**

## Gen IIIA: Field Development Unit

- Existing unit: LCROSS Engineering Test Unit
- Spectral range between 1.3 and 2.3  $\mu\text{m}$ , with S:N >500 and spectral resolution of  $\sim 35$  nm
- Mass: 1.5 kg
- Power: 2.8 W

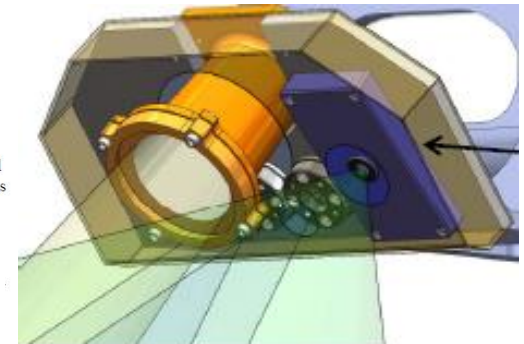
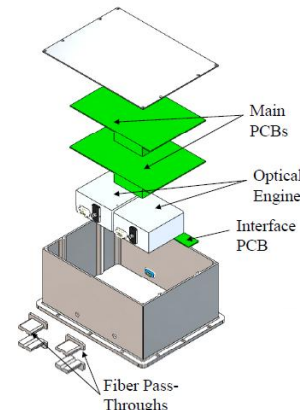
### **Surface Mineral/Volatile Evaluation Near Infrared Volatile Spectrometer Subsystem (NIRVSS) - ARC**

- Measure surface bound OH/H<sub>2</sub>O while traversing (at min. of 0.5% by mass)
- Detect form of water (ice/hydration) in auger tailings
- Detect water vapor in evolved gases
- Image surface and drill tailings



## Gen IIIB: Engineering Test Unit

- Spectral range between 1.8 and 3.2  $\mu\text{m}$  with a spectral resolution of  $< 0.05$   $\mu\text{m}$ .
- Achieve SNR  $\geq 100$  at 3  $\mu\text{m}$  while drilling
- Quantify amount of water in lunar regolith at a minimum abundance of 0.5% by mass
- Identify surface bound H<sub>2</sub>O/OH at rover speed  $\leq 10$  +/- 1 cm/s
- Image drill area with sufficient Field Of View to observe 22 cm of tailings with resolution at  $\sim 200$  mm scale
- Mass: 7.7 kg (NIR, camera, & lamp)
- Power: 16.31 W ave





**Purpose: Develop a flight-like unit that can fit on a rover and operate in the lunar environment**

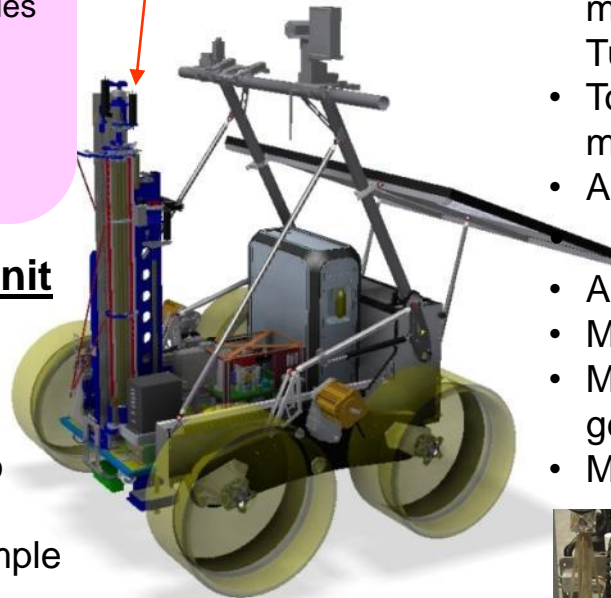
## Sample Acquisition System

### Auger/Core Drill Subsystem [CSA]

- Collect and transfer subsurface material down to 1 m below surface
- Maintain sample stratigraphy and volatiles (below 150 K)
- Meter samples for processing
- Auger material to surface for evaluation
- Measure geotechnical properties of regolith during drilling

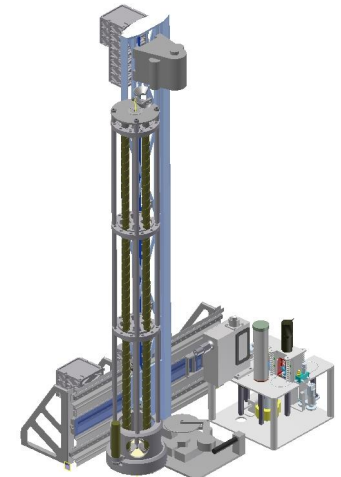
## Gen IIIA: Field Development Unit

- Penetrate substrate 1 m to collect, retrieve, transfer samples from granular material (Push Tube)
- Auger material from 0.5 m depth to surface for evaluation
- Acquire and transfer to 90% of sample from core to Sample Transfer Receptacle (STR) and from STR to OVEN; 16 mm dia. by 12.5 mm length
- Provide windows for sample imaging
- Tested up to 10° slope
- Mass <40 kg
- Power <150 W ave



## Upgrades Required

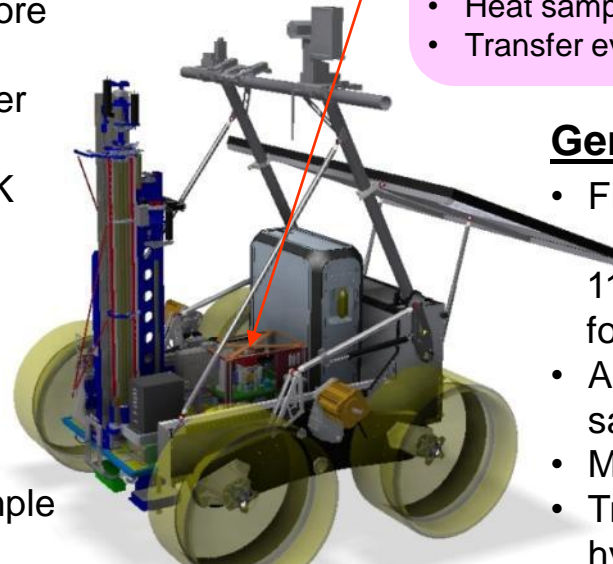
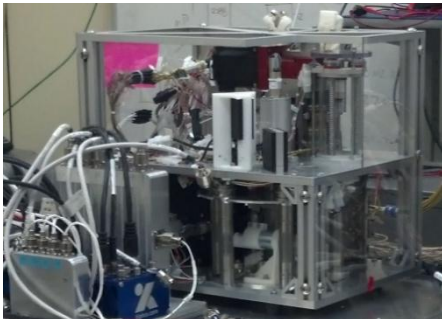
- FDU Capabilities plus the following:
- Penetrate and acquire sample in all media: granular to icy regolith (Push Tube and Core Drill)
- Tool handling and change-out mechanism
- Abandon drill rod and recover
- Operate up to 15° slope
- Autonomous operation
- Measure temperature near core
- Measure while drilling to understand geotechnical properties
- Mass <40 kg (25 kg Goal)



**Purpose: Develop a flight-like unit that can fit on a rover and operate in the lunar environment**

## Gen IIIA: Field Development Unit

- Heat multiple samples to 423 K (150 °C) for volatile extraction
- Accept granular material or solid core sample (16 mm dia. by 125 mm ; 25 to 60 gms) from Sample Transfer Receptacle (STR)
- Transfer volatiles released at 423 K (150 °C) to LAVA surge tank
- Measure sample mass before and after processing to +/- 1 gm
- Selectively accept and reject sample without processing
- Dump sample after processing to remove a minimum of 95% of sample material
- Mass: 13 kg ; Power: <150 W



## Volatile Content/Oxygen Extraction

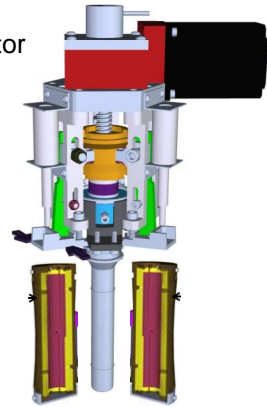
### Oxygen & Volatile Extraction Node (OVEN) - JSC

- Accept samples from Sample Acquisition System
- Heat samples from <150 K to 423K for volatile extraction
- Heat samples to 1173 K for oxygen extraction
- Transfer evolved gases to LAVA volatile analyzer

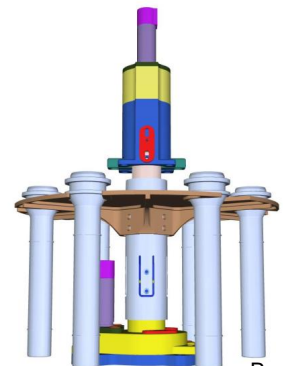
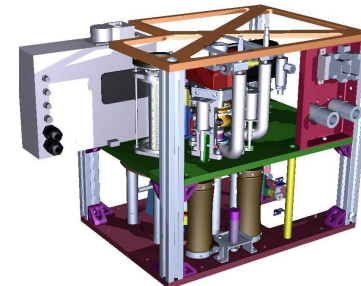
## Gen IIIB: Engineering Test Unit

- FDU Capabilities plus the following:  
Heat a minimum of one sample to 1173 K (900 °C) in presence of hydrogen for oxygen extraction from regolith
- Accept samples at <150 K & maintain samples at <175 K prior to sealing.
- Measure sample mass to +/- 0.1 gm
- Transfer volatiles released during hydrogen reduction to LAVA
- Mass: 10 kg
- Power: <300 W ave.

Crucible-Reactor Configuration



Crucible & Clamshell Heater

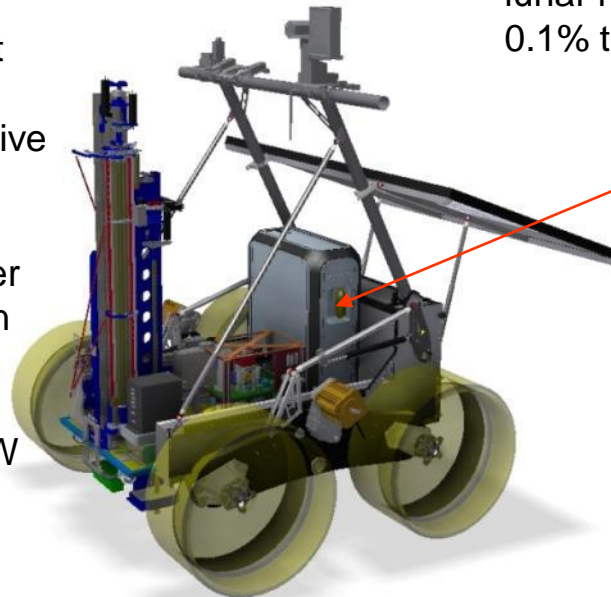
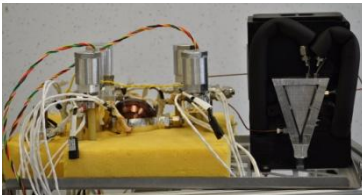




**Purpose: Develop a flight-like unit that can fit on a rover and operate in the lunar environment**

## Gen IIIA: Field Development Unit

- Modified Commercial Off-The-Shelf (COTS) gas chromatograph/mass spectrometer unit
- Accept gas samples from OVEN at up to 100 psi and 423 K (150 °C)
- Identifying and measuring the relative abundance of the evolved volatile constituents to 65 AMU
- Collect and provide images of water collected through volatile extraction and hydrogen reduction of regolith
  - Mass: <37 kg
  - Power: <208 W

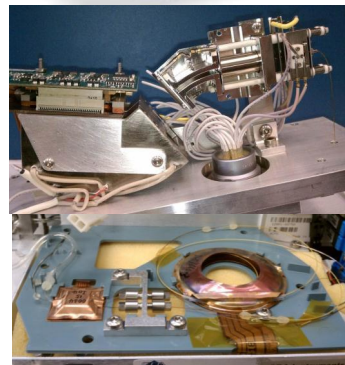


## Gen IIIB: Engineering Test Unit

- FDU Capabilities plus the following:
- Quantify amount of evolved water in from the lunar regolith at a vapor concentration of 0.1% to 95% with a standard deviation of 5%

### **Volatile Content Evaluation** **Lunar Advanced Volatile Analysis (LAVA) - KSC**

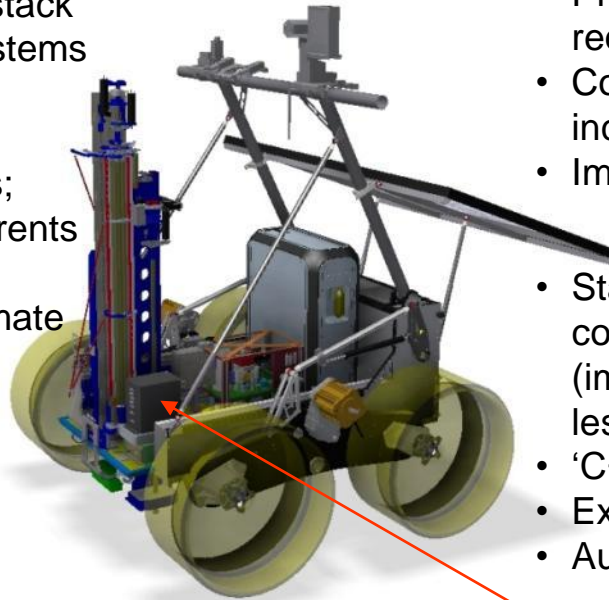
- Accept evolved gas from OVEN; provide hydrogen for oxygen extraction
  - Perform analysis in under 2 minutes
  - Measure water content in evolved gas
  - Characterize volatiles of interest (below 70 AMU)
  - Measure D/H and O<sup>16/18</sup> isotopes
  - Capture & image water evolved
- 
- Measure volatile constituents of the lunar regolith to 70 amu
  - Measure the D/H & O<sup>16/18</sup> isotope ratios
  - Accept gas samples from OVEN at up to 100 psi and 1173 K (900 °C)
  - Provide and regulate hydrogen gas to OVEN for Regolith Oxygen Extraction
  - Mass: 15 kg; Power: <100 W ave



**Purpose: Develop a flight-like unit that can fit on a rover and operate in the lunar environment**

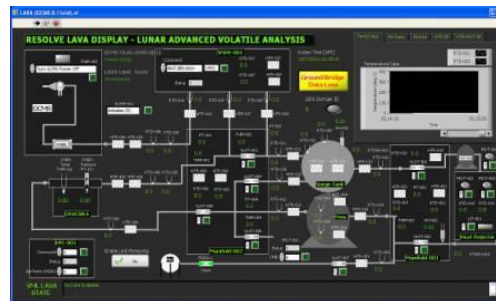
## Field Development Unit (FDU)

- Miniaturized from refrigerator size Engineering Development Unit
- Rugged, configurable slice based stack
- Acquired sensor data from fluid systems
- Controlled motors, heaters, valves, and cameras
- Controlled power to all subsystems; measured GCMS and DESTIN currents
- Managed data bus
- Virtual Machine Language to automate complex sequences
- 'C' programming language based
- CAN bus interface to Avionics
- Simulink generated closed-loop control



## Engineering Test Unit (ETU)

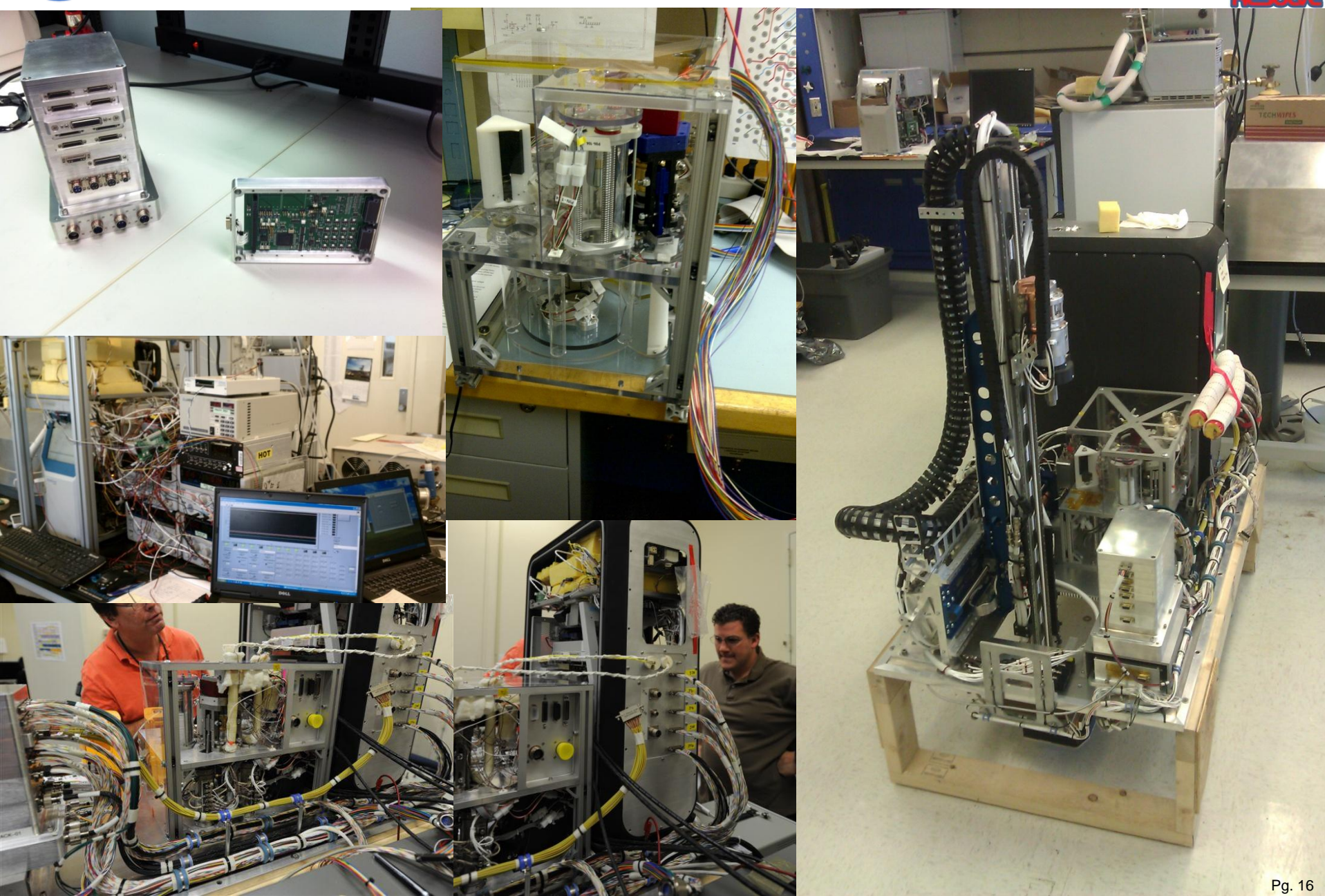
- Test slices for operation in vacuum
- Develop thermal models
- Prototype new circuits to support new I/O requirements
- Component test of key flight components including network switch
- Improve power consumption and improve switching characteristics
- Standardize on components and FPGA controller designs between slices (improve commonality based on FDU lessons learned)
- 'C++' programming language based
- Expanded CAN bus interface to Avionics
- Automate all sequences



## **Operation Control Flight Avionics - KSC**

- Space-rated microprocessor
- Control subsystems and manage data
- Payload level operation coordination
- Reactive control logic to monitor & react to out of limit conditions
- Component, subsystem & system level health monitoring & reporting











# RESOLVE AES/OCT Project Status



## Gen IIIA: Field Development Unit (FDU)

▪ FDU System Requirements Review	03/03/11	<b>Completed</b>
▪ FDU 30% Design Review	05/25/11	<b>Completed</b>
▪ FDU 90% Design Review	08/26/11	<b>Completed</b>
▪ FDU 90% Delta Design Review	10/28/11	<b>Completed</b>
▪ Field Demo Subsystem HW Initial Delivery to KSC	02/27/12	<b>Completed</b>
▪ Field Demo HW Integration onto Rover Complete	06/29/12	<b>Completed</b>
▪ Field Demo HW Delivered to Field Test Location	07/09/12	<b>Completed</b>
▪ Demonstrate Integrated RESOLVE ops on Rover in Field Test	07/27/12	<b>Completed</b>
▪ <i>AES Project Continuation Review</i>	09/18/12	<b>Completed</b>

## Gen IIIB: Engineering Test Unit (ETU)

▪ ETU SRD Initial Delivery	12/16/11	<b>Completed</b>
▪ Complete ETU System Requirements Review	08/29/12	<b>Completed</b>
▪ ETU 30% Design Review	12/14/12	
▪ ETU 90% Design Review	07/26/13	
▪ <i>AES Project Continuation Review</i>	09/13	
▪ <i>OCT Project Evaluation/Continuation Review</i>	09/13	
▪ ETU Subsystem Environment Testing Complete	05/12/14	





# RESOLVE Development Plan Thru 2014



- Reexamine RESOLVE Design Reference Mission (DRM) to finalize rover and lander requirements
  - Examine potential landing sites at north and south pole
  - Focus on roles of lander and rover on power generation and storage, communications with Earth, and thermal management
- Baseline RESOLVE Instrument Suite requirements
- **Perform lunar vacuum/environment risk reduction and flight prototyping**
  - Develop flight prototypes of Near IR and Neutron Spectrometer, and LAVA gas chromatograph/mass spectrometer
  - Develop flight development units for of OVEN reactor and LAVA subsystems
  - Perform integrated test of OVEN and LAVA subsystems under lunar environmental conditions
- Work with Canadian Space Agency (CSA) on developing sample acquisition system and rover for potential future mission
- Work with NASA and CSA science on involvement and instrument suite



# RESOLVE POLAR MISSION ANALOG FIELD TEST & RESULTS



# 3rd International ISRU Analogue Field Test

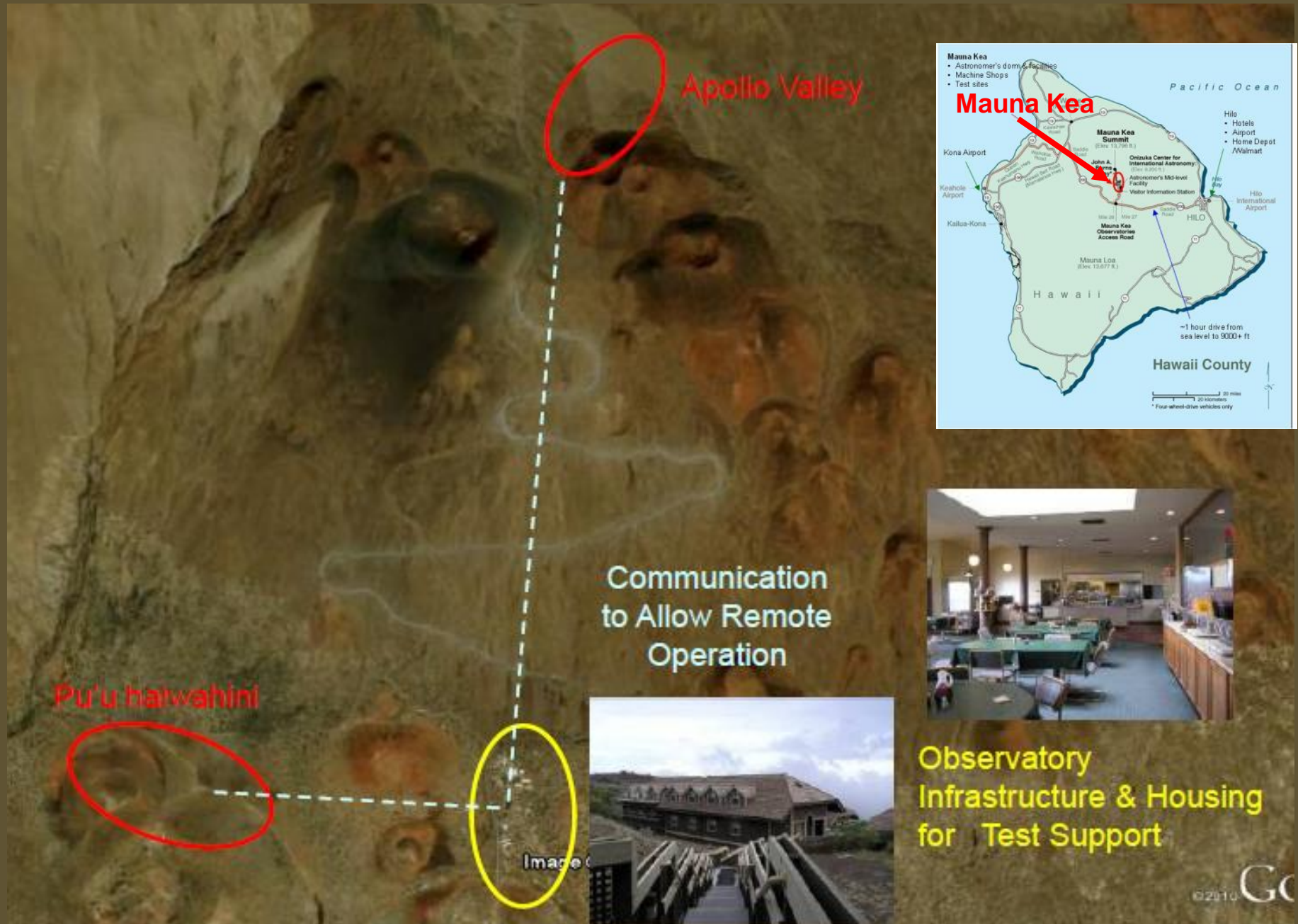


July 10 – 24, 2012  
Mauna Kea, Hawaii

## Focus on 1<sup>st</sup> Step in Space Mining Cycle - Prospect

- **Objective 1: Demonstrate Integrated Mobility Platform/Science Payload for Lunar Polar Ice/Volatile Mission (RESOLVE Mission)**
  - **Rationale: 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 scientific investigations of terrain, geology, and resources before crews arrive (SMD - Moon Mars Analog Mission Activity)**
  - **Rationale: Science goals and instruments are synergistic with ISRU prospecting**

# Analogue Test Locations on Mauna Kea





# Test Site on Hawaii Very Much Like the Moon!

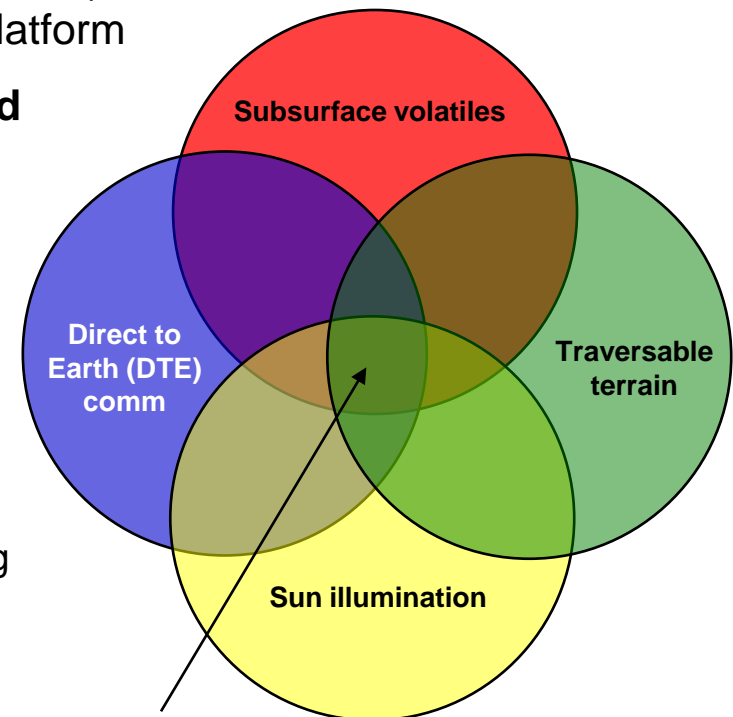




# Objective 1: Demonstrate Integrated Mobility Platform/Science Payload for Lunar Polar Ice/Volatile Mission

**Mission Simulation Purpose:** Perform mission scenarios remotely with all hardware/capabilities required for actual lunar mission

- **Demonstrate integration** (physical, data, power, command) of all hardware necessary for flight mission on mobile platform
- **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 remote mission command and control** (with lunar time delays and bandwidth limitations)



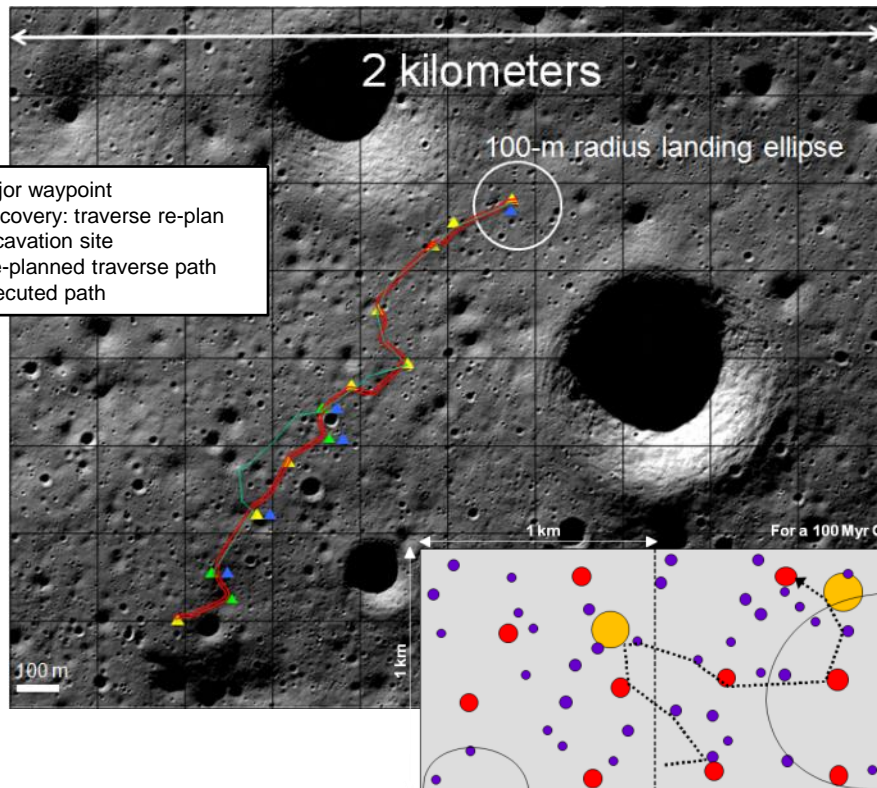
- **5 – 9 day surface mission**
- **Sunlight with shadowed areas**
- **Earth viewing**
- **<100 K subsurface temperature**

## 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.



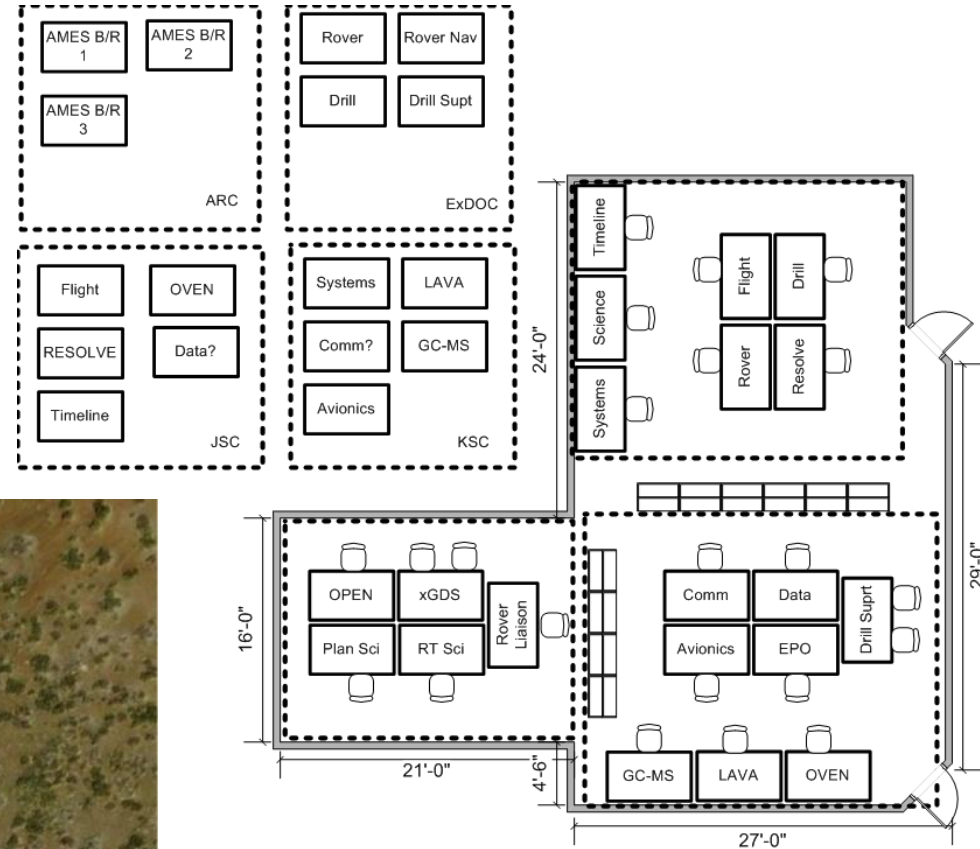
## CAT 3 Objectives (Desirable)

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

- All RESOLVE & rover operations initially controlled by ops center in Hale Pohaku
- Rover control transitioned to ExDOC at CSA HQ
- Sample processing operations transitioned to KSC/JSC at end of test day in Hawaii
- ARC science room to support both real-time science and science planning

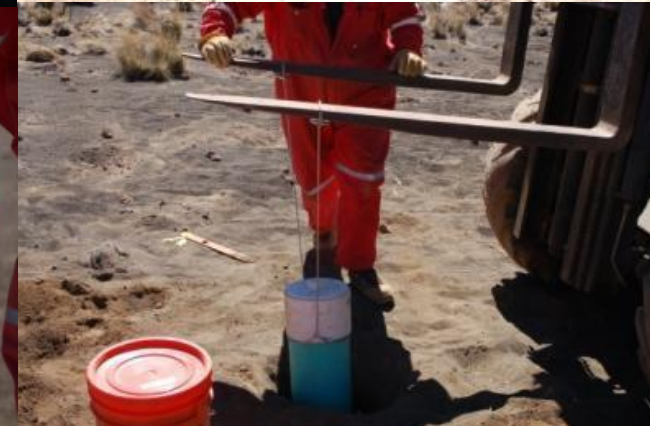


‘Flight control’ rooms in Hawaii, Houston, Kennedy, and Montreal. Science room at Ames

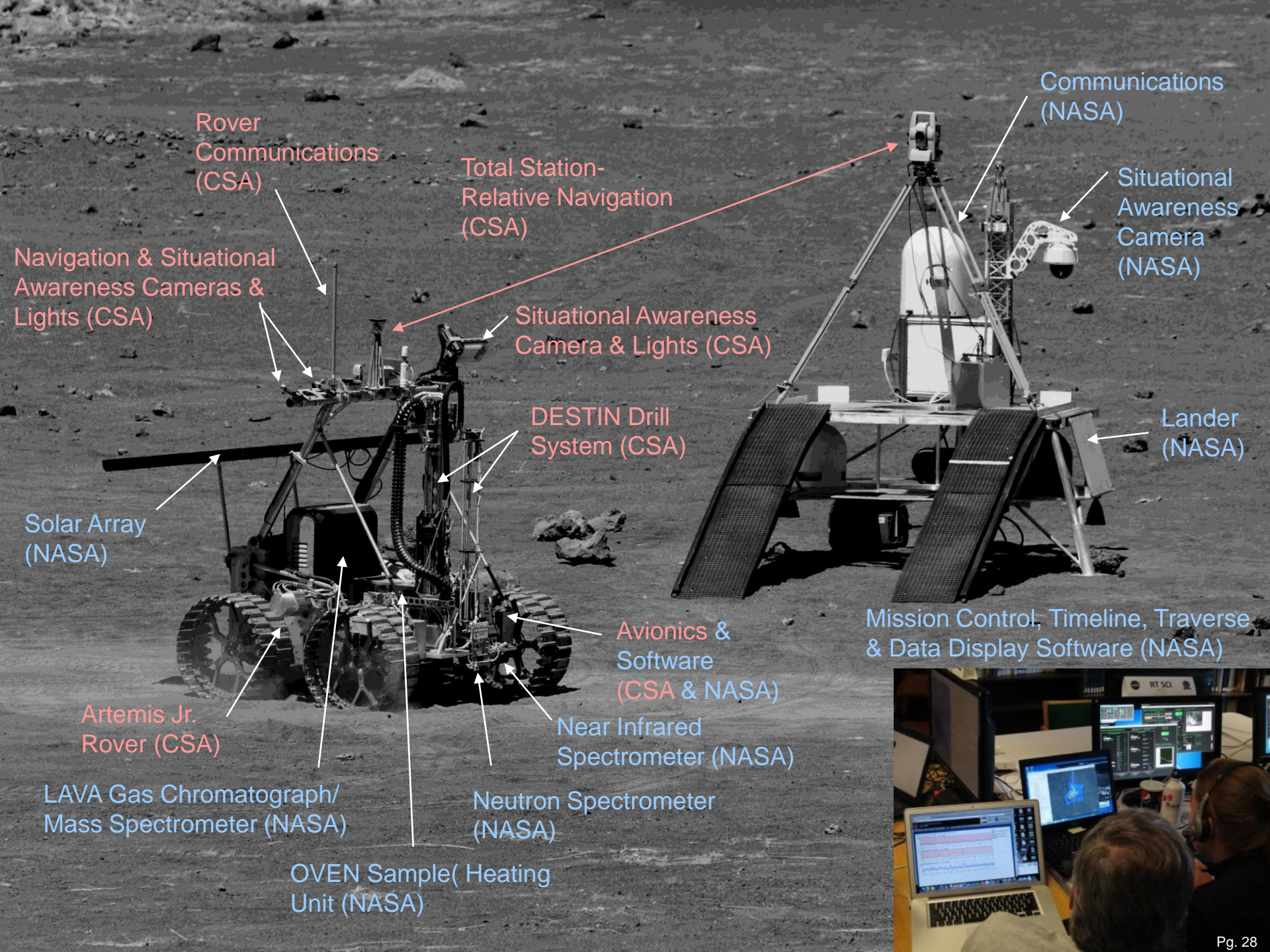
Traverse path with simulated water/ice targets hidden along path

Google earth









Rover  
Communications  
(CSA)

Total Station-  
Relative Navigation  
(CSA)

Communications  
(NASA)

Situational  
Awareness  
Camera  
(NASA)

Navigation & Situational  
Awareness Cameras &  
Lights (CSA)

Situational Awareness  
Camera & Lights (CSA)

DESTIN Drill  
System (CSA)

Lander  
(NASA)

Solar Array  
(NASA)

Mission Control, Timeline, Traverse  
& Data Display Software (NASA)

Avionics &  
Software  
(CSA & NASA)

Artemis Jr.  
Rover (CSA)

Near Infrared  
Spectrometer (NASA)

LAVA Gas Chromatograph/  
Mass Spectrometer (NASA)

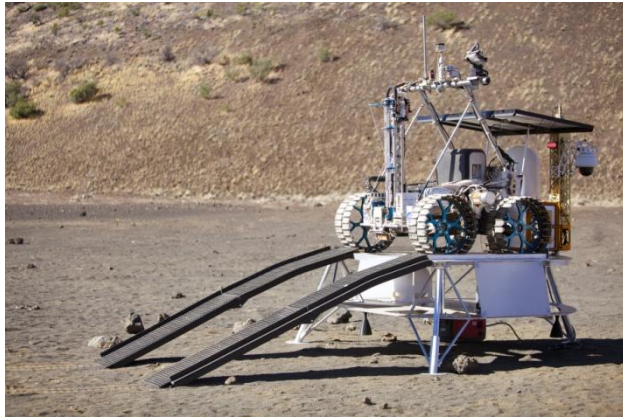
Neutron Spectrometer  
(NASA)

OVEN Sample( Heating  
Unit (NASA)

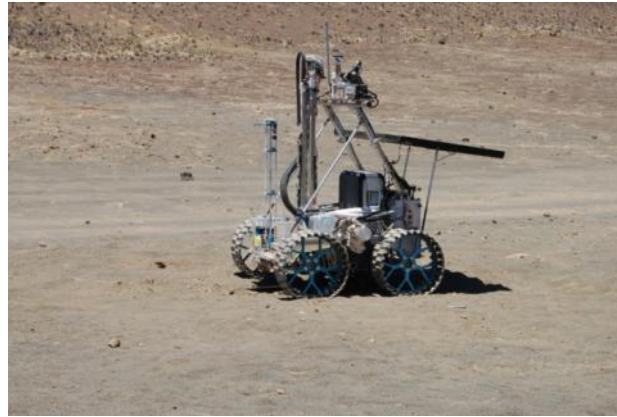




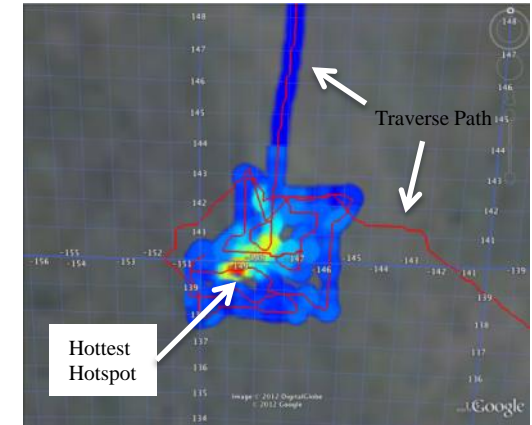
'Flight' like hardware and operations



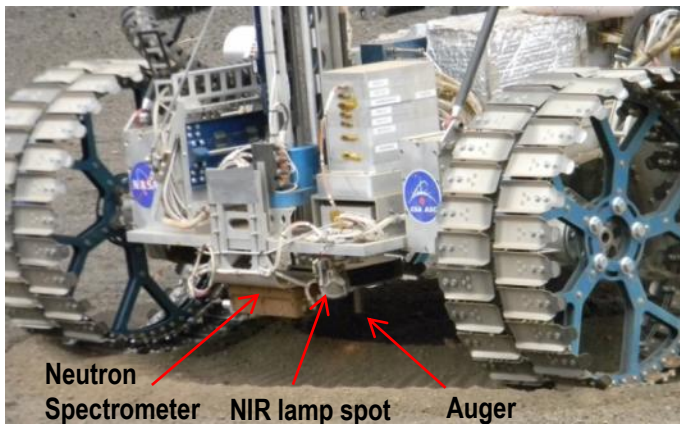
Rover Egress from Lander



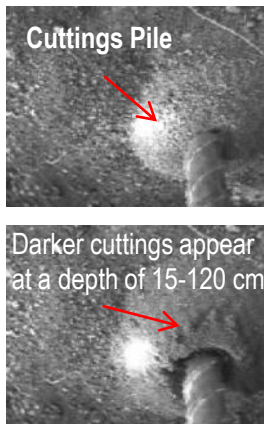
Rover Searching Exploration Site



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

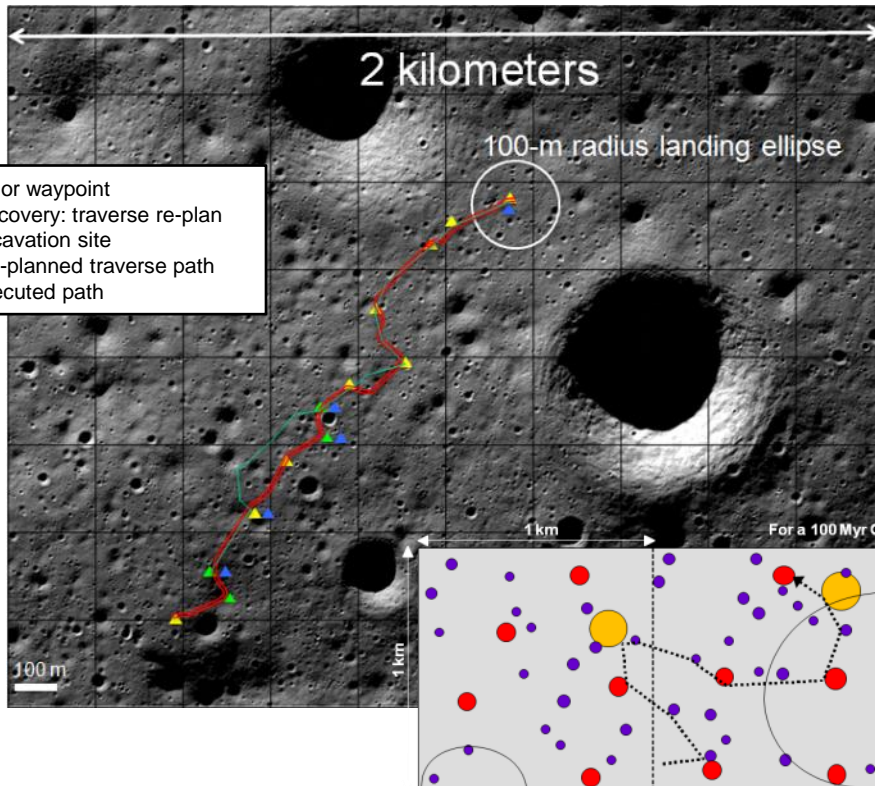


## CAT 1 Objectives (Mandatory)

- ✓ Travel at least 100m on the lunar surface to map the horizontal distribution of volatiles (FD1)

## CAT 2 Objectives (Highly Desirable)

- ✓ Perform at least 1 coring operation. Process all regolith in the drill stem acquired during the coring operation. (FD2)
- ✓ Perform at least 1 water droplet demo during volatile analysis. (FD2)



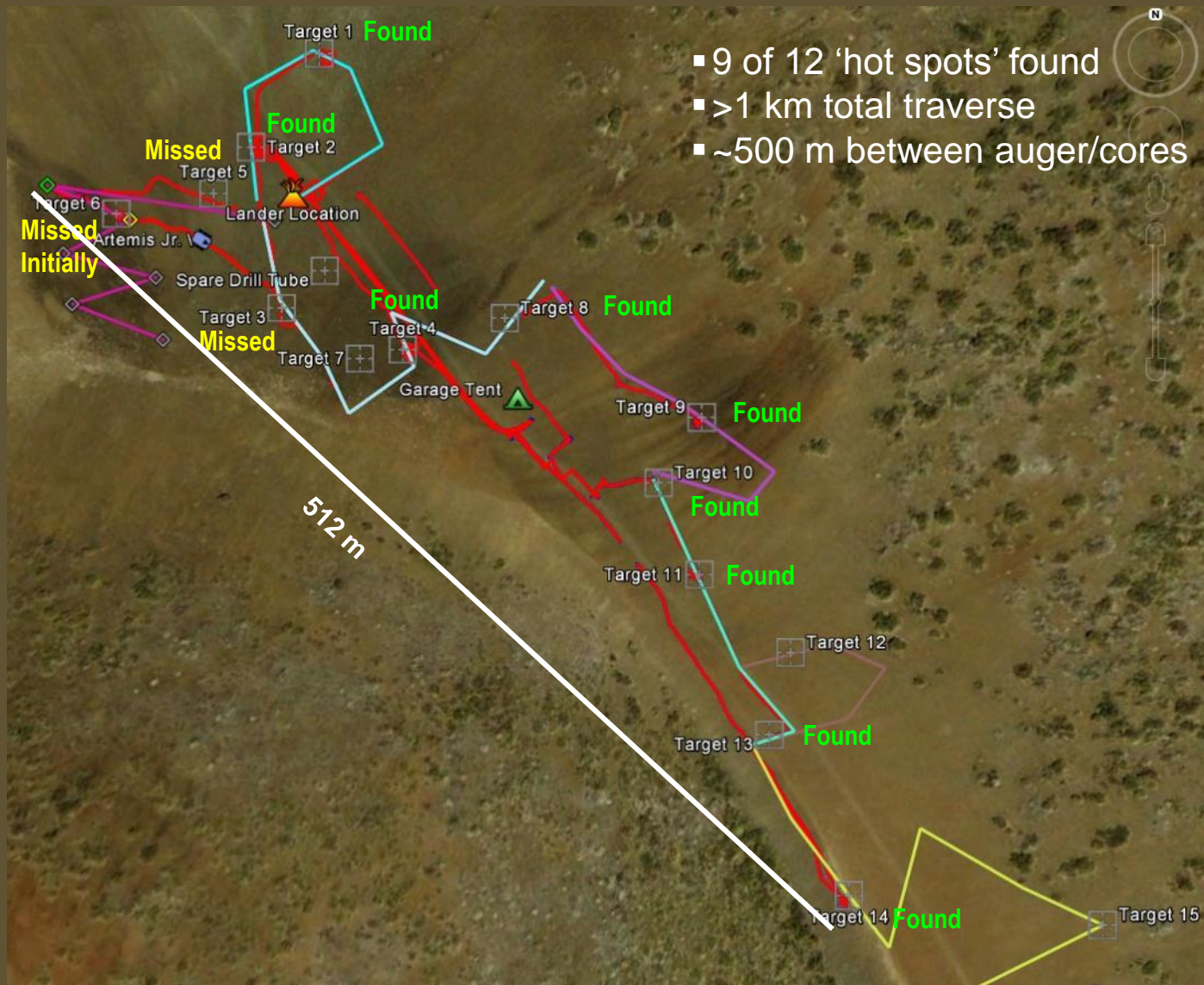
## CAT 3 Objectives (Desirable)

- ✓ Map the horizontal distribution of volatiles over a point to point distance of 500m (FD4) (lunar objective is 1km.)
- ✓ Perform coring operations and process regolith at a minimum of 3 locations. (FD4)
- ✓ Volatile analysis will be performed on at least 4 segments from each core to achieve a vertical resolution of 25cm or better.
- ✓ Perform a minimum of 3 Augering operations (FD4). (Note that the Lunar objective is 6)
- ✓ 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)

- ✓ Perform 2 coring operations be separated by at least 500 m straight line distance. (FD7) (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
- ✓ Perform hardware activities that can be used to further develop lunar exploration technologies (FD7)

# Complete RESOLVE Mission Traverse





# RESOLVE Mission Simulation Accomplishments



- **Completed 7 analogue test days** (used Contingency Day due to issues)
- **Demonstrated mission objectives and operations for a short duration lunar polar ice/volatile characterization mission:**
  - **Demonstrated all operations and phases to mission post landing:**
    - i) rover egress from lander, ii) rover traverse, iii) hot-spot localization, iv) augering, core acquisition, and transfer, v) core processing and volatile characterization
    - New mission mode identified and demonstrated: examine core by dropping on ground while rover moving and examine with NS and NIR
  - **Demonstrated communication and operations associated with lunar robotic precursor mission**
  - **Demonstrated multi-shift and multi-command center operations that may be needed for a future around-the-clock 7 day mission**
    - Artemis Jr. controlled from field, HP, and ExDOC
    - RESOLVE payload controlled from HP, JSC, and KSC
    - Science backroom support from ARC
    - Operations shifted from HP to mainland to extend test day and operations
  - **Demonstrated use of Exploration Ground Data System (xGDS)** for mission planning, traverse path following, and data layering and display
  - **Demonstrated capability of Playbook for mission timeline/procedures**





# RESOLVE Mission Hardware Accomplishments



- **Artemis Jr. Rover**
  - Tele-operation control rover from HP rover consoles, in the field, and from ExDoc.
  - Autonomous mode traverse performed; 250 m
  - Total in-simulation roving distance at end of mission: 1140m
- **Near IR & Neutron Spectrometer**
  - Site location and mapping performed with near infrared spectrometer and neutron spectrometer
  - Team found 9 hot spots and missed 3 (due to rover deviating from planned traverse).
    - 7 Hotspot localization procedures performed
- **DESTIN drill subsystem**
  - Demonstrated rotary (auger), percussive (push tube), and rotary/percussive (auger) modes of operation
  - 4 auger operations: 3 in native material; 1 in drill tube
  - 4 push tube drill operations: 3 in drill tube, one in native material (Mars like)
  - Push tube drilled to 90 cm: ~75 cm of sample captured (211 gms) achieving 80% fill requirement
  - Demonstrated sample transfer from push tube to OVEN: 22.76, 26.0, 17.7, & 38.2 gms transferred
- **OVEN sample heating subsystem:**
  - 4 core segments heated and processed; Manual and VML script processing demonstrated
    - 150° C achieved
    - 64, 65, 80, 73 psi pressure achieved before evolved volatile gas transfer to LAVA
  - Multiple gas transfers from OVEN to LAVA
  - Demonstrated H<sub>2</sub> Reduction operation (in lab.)
- **LAVA volatile characterization subsystem:**
  - 2 separate push tube cores evaluated
    - 3 core segments evaluated for water/volatiles released
    - 4 transfers from a high water content sample and proceeded to utilize a flow through method to demonstrate the capability to handle high water samples within a reasonable timeline
  - 2 water droplet demonstrations performed



# RESOLVE Mission Major Lessons Learned



- **Need to perform more training and mission simulations again in the future (virtual or real) to develop products, operations and procedures to meet timeline efficiency expectations for a 7 day mission**
- **Need to examine options and modifications to speed up moving operations for sample acquisition/transfer and volatile oven subsystems**
- **Design of volatile oven subsystem may be overly complex based on mission requirements – Need to reevaluate both design and requirements**
- **Discovered that new approach for volatiles analysis may be required for high water content samples**

# RESOLVE MISSION 2012



## Questions?





# BACKUP



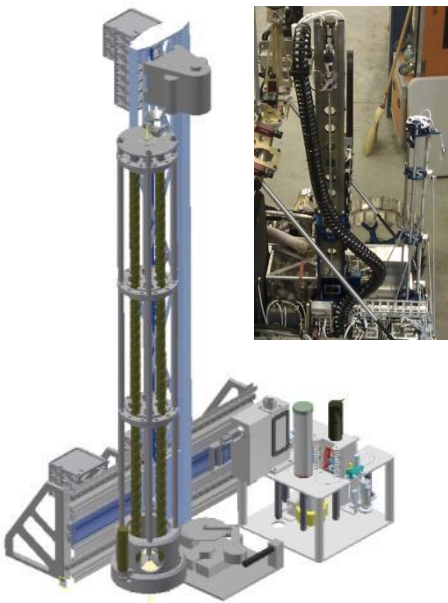
# Key RESOLVE Mission Design Trades



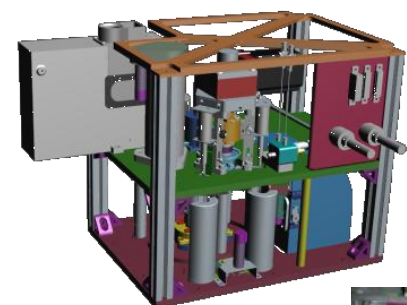
Mission Attributes	Base	Mid	Full
Location	Long duration sunlight	<b>Min. Sun/Shadowed</b>	Permanent Shadow
Sample Site Selection	Surface features/minerals	<b>Neutron Spec on Rover</b>	Neutron Spec with GPR
Subsurface Sample Acquisition	Arm/scoop	<i>Auger w sample transfer</i>	<b>Core Drill/Push Tube w sample transfer</b>
Sample of Interest	Rock/regolith	Ice	<b>Polar volatiles</b>
Sample Depth	<i>&lt;0.75 m</i>	<b>1.0 m</b>	2.0 m
Sample Measurement	Downhole Optical for ice	Oven w Tunable Diode Lasers	<b>Oven with GC/MS and Near IR</b>
Sample Preparation	<b>None</b>	Crushing	Thin Section
Mineral Characterization	None	<b>Single instrument - Near IR</b>	Multiple Instruments
Regolith/Dust Physical Characterization	None	<b>Camera &amp; Drill Response</b>	Microscope & Geotechnical Instruments
Volatile/Product Collection	None	<b>Water</b>	Water and gas volatiles
Oxygen Extraction from Regolith	None	<b>H<sub>2</sub> Reduction w Same Oven</b>	Separate demo
Temperature/Radiative Environment Characterization	None	<b>External temp sensor</b>	Instrumented Radiator
Mobility	None - Lander	Hopper	<b>Rover</b>
Power	<i>Non-recharge battery</i>	<b>Battery/Solar Array</b>	Nuclear
Communications	<b>Direct to Earth-rover</b>	<i>Direct to Earth-lander; rover relay</i>	Comm Relay Satellite

**Blue Bold** = Baseline

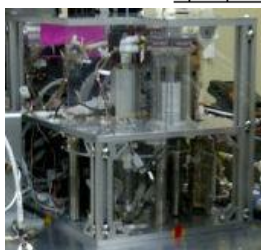
*Red Italics* = Backup



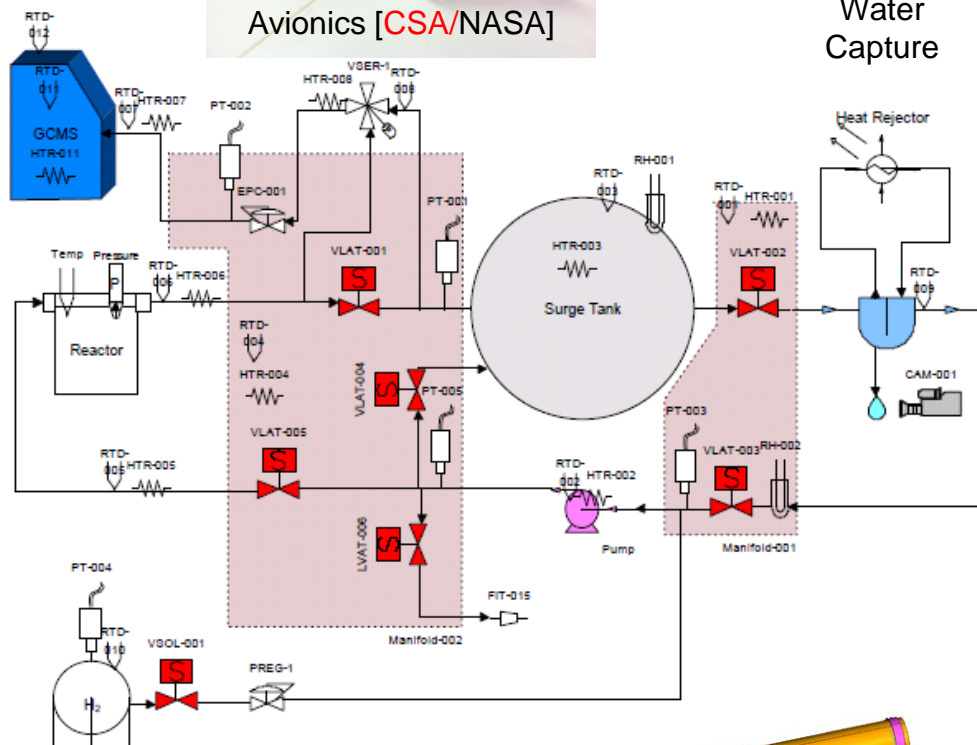
1 m Drill & Sample Metering  
[CSA]



Oxygen & Extraction  
Node (OVEN)



Avionics [CSA/NASA]



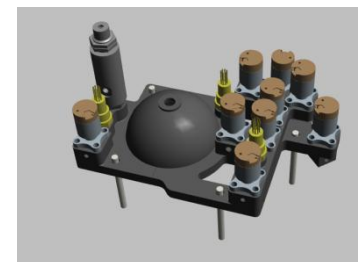
Neutron Spectrometer



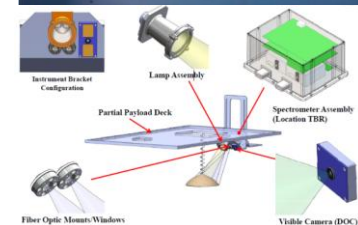
Water  
Capture



Gas Chromatograph -  
Mass Spectrometer



Surge Tank and Fluid  
Manifolds



Near Infrared  
Spectrometer





# Analog Field Test Participants



## RESOLVE Lunar Polar/Ice Characterization Mission Simulation

- NASA – Onsite in Hawaii and Mainland Operations: HQ, KSC, JSC, & GRC
  - MSFC and Teledyne Brown for mockup lander
- CSA – Onsite in Hawaii and ExDOC at CSA HQ
- Neptec and Ontario Drive & Gear (Artemis Jr. Rover)
- Northern Centre for Advanced Technology – NORCAT and Electric Vehicle Controllers (DESTIN Drill System and analogue support)
- Xiphos (RESOLVE electronics)
- COM DEV, NGC Aerospace, McGill University, Proto Innovations, & Provectus



# Neutron Spectrometer Subsystem (NSS) Functions & Design Constraints



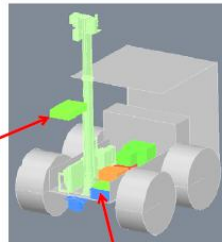
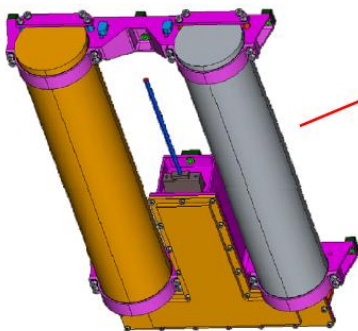
## NSS Functions

- Determine the horizontal and vertical distribution of hydrogen and hydrogen bearing compounds/minerals
  - Map to 1 meter depth and ~ 1 m wide path
  - Map to depth at rover speed  $\leq 10 \pm 1$  cm/s
- Detect water at a minimum abundance of 0.5% by mass with <10% uncertainty
- Operate  $\geq 6$  hrs in permanently shadowed area

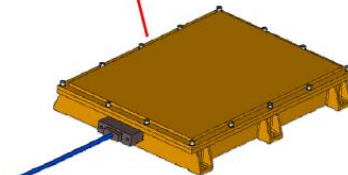
## NSS Design Constraints

- Mount ~1 m above the surface aimed in front of the rover
- Operate -30 to +40 °C
- Max temperature change rate: 20 °C /hour
- Instrument Mass: 1.85 kg
- Power: 2 W ave.; <4 W max for heaters

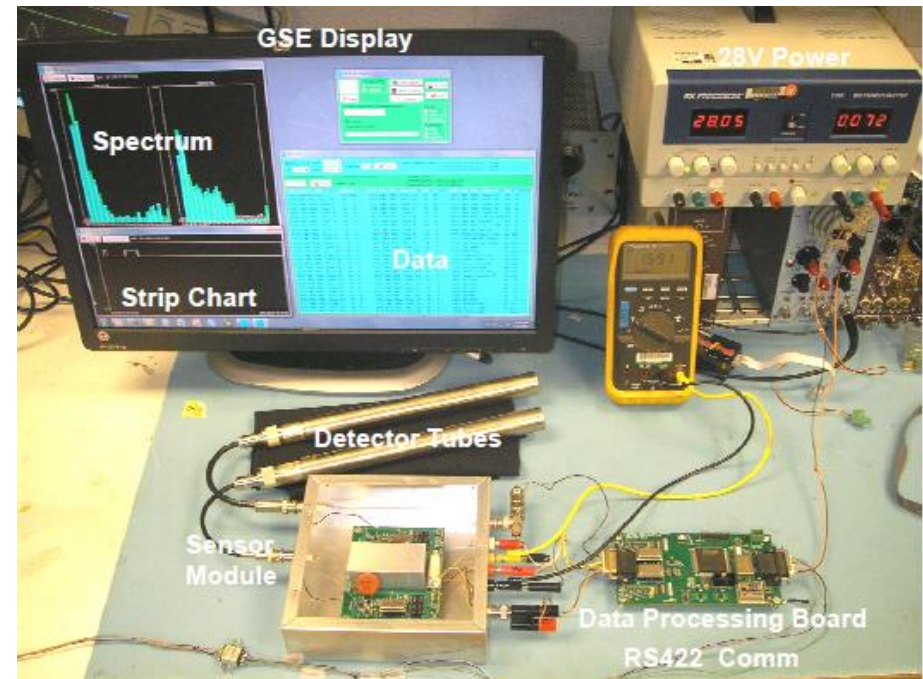
NSS Sensor Module (SM)  
On boom or fixed structure



NSS Data Processing Module (DPM)  
Integrated within main payload



## NSS Brassboard





# Near Infrared Volatile Spectrometer Subsystem (NIRVSS) Functions & Design Constraints

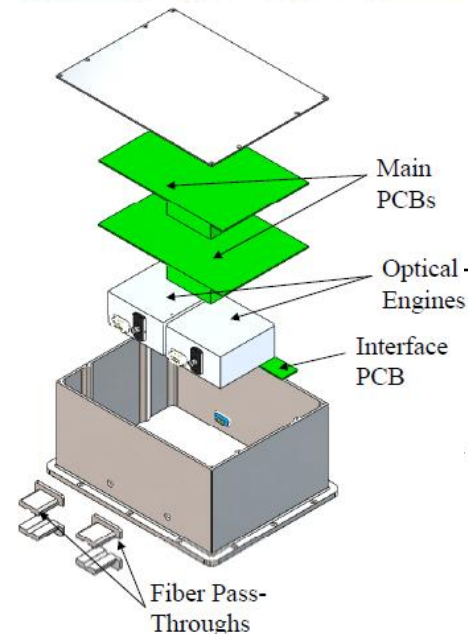
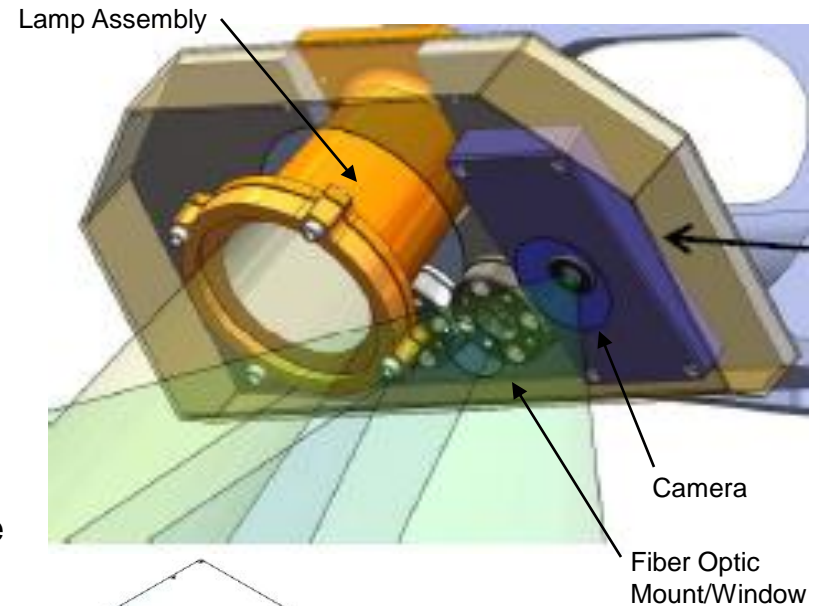


## NIRVSS Functions

- Quantify amount of water in lunar regolith at a minimum abundance of 0.5% by mass
- Identify surface bound  $\text{H}_2\text{O/OH}$ 
  - Map at rover speed  $\leq 10 \pm 1$  cm/s
- Bound understanding of mineral content in regolith
- Identify volatiles, including water content and form evolved during auger/drilling
- Bound volatile presence in top 20-30 cm of regolith during auger/drilling
- Enable observation under all lighting conditions
- Image drill area with sufficient Field Of View to observe 22 cm of tailings with resolution at  $\sim 200 \mu\text{m}$  scale
- Operate  $\geq 6$  hrs in permanently shadowed area

## NIRVSS Design Constraints

- Identifying volatile and mineralogical features in the near-infrared spectrum in the range of 1.8-3.2 microns with a spectral resolution of less than  $0.05 \mu\text{m}$ .
- Mount Near IR, Camera, and lamp to view auger/drill area
- Achieve  $\text{SNR} \geq 100$  at  $3 \mu\text{m}$  while drilling
- Operate  $+0$  to  $+45^\circ\text{C}$
- Mass: 7.7 kg
- Power: 16.31 W ave (NIR, camera, & lamp)



Spectrometer Assembly





# Sample Acquisition Subsystem: DESTIN Functions & Design Constraints

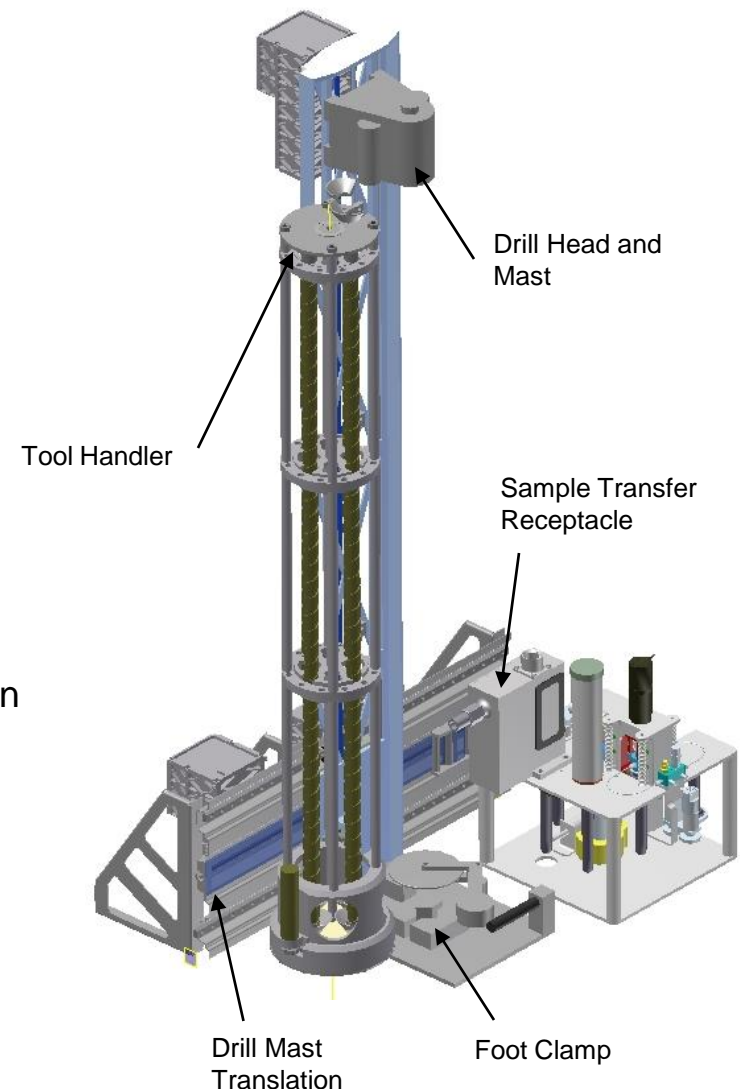


## DESTIN Functions

- Penetrate substrate 1m to collect, retrieve, transfer samples from  $>0.75$  m
  - Unconsolidated regolith to consolidated
- Auger material to surface from depth up to 0.5 m
- Maintain sample phase, chemical state, and stratigraphy
- Sample Transfer Receptacle (STR)
  - Section samples to 12.5 cm length x 1.6 cm dia.
  - Deliver  $\geq 90\%$  of sample to OVEN
  - Deliver sample to OVEN at  $<150$  K
- Minimize sample cross-contamination
- Abandon drill rod if stuck and recover
- Autonomous operation in shadowed region for  $\geq 6$  hrs
- Measure temperature near core
- Measure: sample hardness, energy required for penetration, rate of cut, drill depth, instantaneous drilling power, weight on bit, torque, rpm

## DESTIN Design Constraints

- Dimensions of all components  $<1.35\text{m} \times 0.75\text{m} \times 1\text{m}$
- Safe position must not interfere with rover locomotion
- Operate when tilted up to 15 degrees
- No consumables
- 50 auger/drill operations
- Mass:  $<40$  kg max.; 25 kg goal
- Power:  $<150$  W ave.
- Static Force: 120 N max.



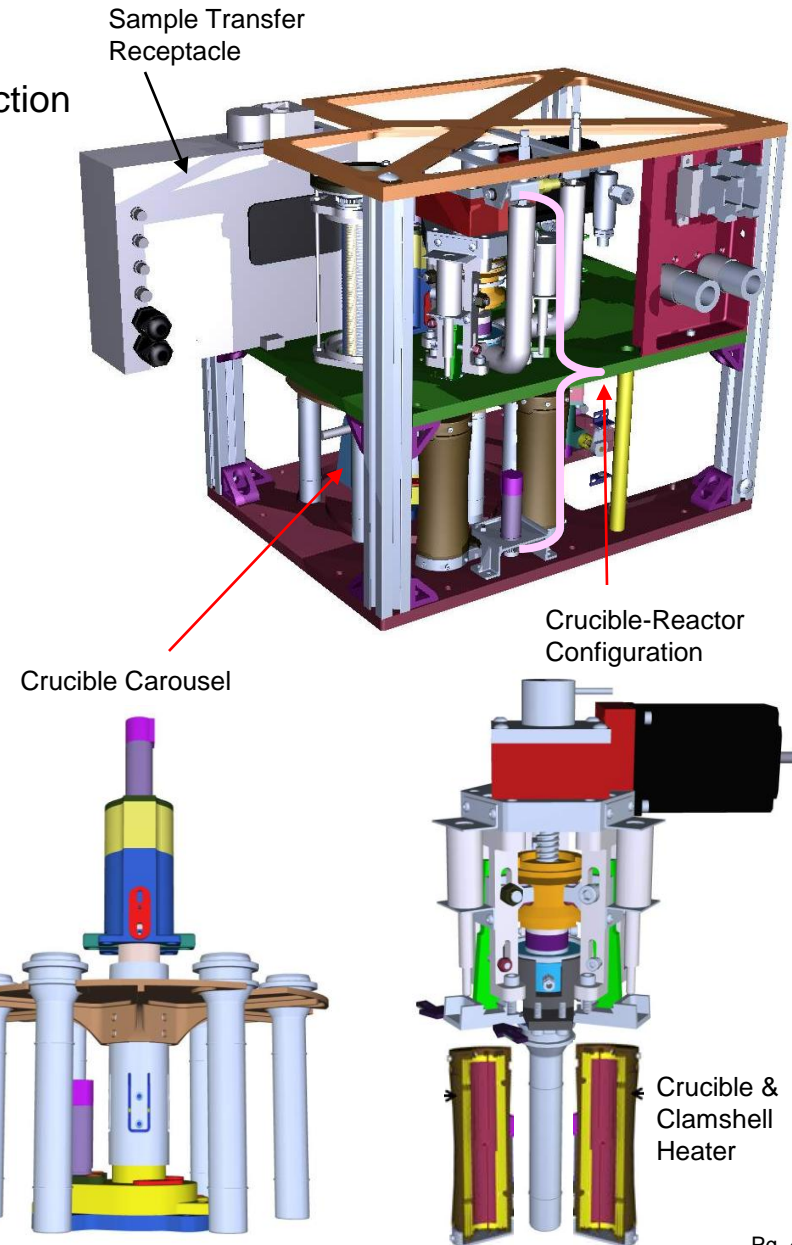
# Oxygen and Volatile Extraction Node (OVEN) Functions & Design Constraints

## OVEN Functions

- Heat multiple samples to 423 K (150 °C) for volatile extraction
- Heat a minimum of one sample to 1173 K (900 °C) in presence of hydrogen for oxygen extraction from regolith
- Accept sample from Sample Transfer Receptacle (STR)
  - May be solid core or granular material:  
16 mm dia. by 125 mm ; 25 to 60 gms
- Accept samples at <150 K
- Maintain samples at <175 K prior to sealing.
- Measure sample mass before and after processing to +/- 0.1 gm accuracy
- Dump sample after processing to remove a minimum of 95% of sample material
- Selectively accept and reject (dump) sample without processing
- Transfer volatiles released (at 150 and 900 °C sample temperatures) to surge tank in analysis and water droplet demo.

## OVEN Design Constraints

- Minimum leak rate during sample processing - psi over 4 hrs at 100 psi (at 150 and 900 °C)
- Heat 40 samples in 5-7 day mission
- Mass: 10 kg
- Power: <300 W ave.
- Minimize height of OVEN subsystem since STR drill tube must extend above OVEN





# Lunar Advanced Volatile Analysis (LAVA) Functions & Design Constraints

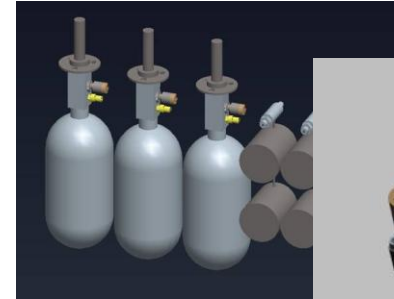


## LAVA Functions

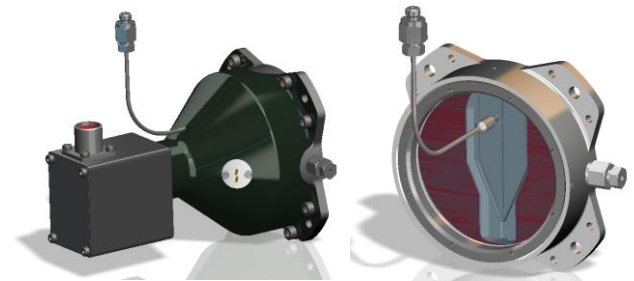
- Accept gas samples from OVEN at up to 100 psi and 423 K (150 °C) to 1173 K (900 °C)
- Identifying and measuring the relative abundance of the volatile constituents of the lunar regolith.
  - Quantify amount of evolved water in from the lunar regolith at a vapor concentration of 0.1% to 95% with a standard deviation of 5% relative standard deviation or the absolute standard deviation of 0.2% water , whichever is greater
  - Measure volatile constituents of the lunar regolith to 70 amu including, CO, H<sub>2</sub>O (g), H<sub>2</sub>, [H<sub>2</sub>S, NH<sub>3</sub>, SO<sub>2</sub>, C<sub>2</sub>H<sub>4</sub>. are Goals]
  - Measure the D/H and O<sup>16/18</sup> isotope ratios (Goal)
- Collect and provide images of water collected through volatile extraction and hydrogen reduction of regolith
- Provide and regulate hydrogen gas to OVEN for Regolith Oxygen Extraction

## LAVA Design Constraints

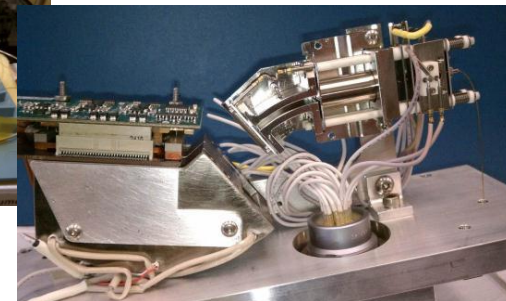
- Complete GC-MS analysis in under 2 minutes
- Mass: 15 kg
- Power: <100 W ave.



Surge Tank and Fluid Subsystem



Water Droplet Demo w/ Camera



Gas Chromatograph/Mass Spectrometer





# RESOLVE Top-Level Science/ISRU Requirements



- **Measure the water and hydrogen bearing volatiles content in a lunar subsurface**
  - **Determine the horizontal and vertical distribution of hydrogen and hydrogen bearing volatiles**
    - Measure the spatial distribution of hydrogen and hydrogen bearing volatiles with a min. horizontal resolution of 2.0 meters and a minimum vertical resolution of 0.25 m.
    - Measure neutron flux consistent with at least 0.5 wt% water equivalent hydrogen,
    - Measure 0.5 wt% water-equivalent layer at 1 meter depth under a dry overburden, with 25 cm depth resolution
    - Measure spatial OH and H<sub>2</sub>O in the Near IR spectrum
  - **Extract subsurface material**
    - Extract a subsurface sample up to a depth of 0.75 m. (Goal of 1 m)
    - Maintain a minimum of 1 subsurface core segment per core below 175 deg K (-98 deg C)
    - Selectively accept sections of an acquired subsurface sample
    - Obtain augured cuttings from a depth of 0.5 meters
  - **Measure the abundance of water and hydrogen bearing volatiles in the lunar subsurface**
    - Quantify water in the lunar regolith when water concentrations are between 0.5% to 8.0% (95% TBR) by mass
    - Process a minimum of 40 subsurface core segments.
    - Heat lunar regolith samples to a minimum of 425 deg K (150 deg C) for volatile extraction.
    - Identify and measure the relative abundance of the volatile constituents of the lunar regolith below 70 amu
    - Measure the isotope ratio of Deuterium/Hydrogen and Oxygen 16/18
- **Measure geotechnical characteristics of the lunar highlands and cold traps**
  - Measure the distribution of grains in the lunar regolith with respect to size and shape. (GOAL)
  - Measure bulk characteristics of lunar regolith
  - Determining geotechnical parameters of the drilling media during the sample acquisition phase
  - Identifying mineralogical features in the lunar regolith
- **Demonstrate oxygen extraction from regolith using the Hydrogen Reduction process**
  - Heat samples to 1175 K (902 C) to hydrogen reduction
  - Measure water vapor produced
  - Image water condensate/droplets produced during volatile analysis and H<sub>2</sub> reduction



# Lunar Strategic Knowledge Gaps vs RESOLVE Instruments



## Lunar Exploration Strategic Knowledge Gaps

## RESOLVE

### Map and characterize broad features of polar cold traps

#### A. Measure geotechnical characteristics of cold traps

Measure the size and shape distribution of grains in the lunar regolith	Camera imaging
Measure bulk characteristics and geotechnical properties	Measure while drilling

#### B. Measure physiography and accessibility of cold traps

Measure rover angle
Camera imaging

### Determine lateral and vertical distribution and extent of polar volatiles

#### A. Measure concentration of water and other volatiles species within depth of 1-2 m

Extract subsurface sample down to 0.75 m (1.0 m goal)	Sample Acquisition System
Auger cuttings from depth of 0.5 m	Sample Acquisition System
Transfer samples 25 +/- 2 cubic centimeters in volume	Sample Acquisition System
Measure the relative abundance of the volatile constituents of a lunar subsurface regolith sample	OVEN
	Gas Chromatograph/Mass Spectrometer
Quantify the amount of water in the lunar regolith when water concentrations are between 0.5% to 8.0% by mass (TBR).	OVEN
	Gas Chromatograph/Mass Spectrometer
	Near Infrared Spectrometer
	Water Droplet Demo

#### B. Measure variability of water concentration on scales of 10's of meters

Determine the spatial distribution of hydrogen and hydrogen bearing volatiles with a min. horizontal resolution of 2.0 meters and a vertical resolution of 0.25 m.	Neutron Spectrometer
Measure the thermal and epithermal neutron fluxes corresponding to a 0.5 wt% water-equivalent layer at 1 meter depth	Neutron Spectrometer
Traverse the lunar surface with a minimum range of 1 km total point to point separation. (Goal of 3 km)	Rover

#### C. Measure mineralogical, elemental, molecular, isotopic, make up of volatiles

Measure the reflected radiance to +/-25% between (at least) 1.8 and 3.3 microns for mineral and volatile content.	Near Infrared Spectrometer
Perform visual and near infrared inspection of the augured cuttings.	Near Infrared Spectrometer
Measure the isotope ratios of Deuterium to Hydrogen and Oxygen-16 to Oxygen-18	Mass Spectrometer

#### D. Measure physical nature of volatile species (e.g. pure concentrations, intergranular, globular)

Near Infrared Spectrometer
----------------------------

#### E. Measure spatial and temporal distribution of OH and H2O at high latitudes

Measure spatial OH and H2O in the Near IR spectrum	Near Infrared Spectrometer
--	----------------------------

### Measure lunar ISRU production efficiency: Measure the efficiency of ISRU

Heat samples to 1175 K (902 C) to hydrogen reduction.	OVEN
Measure amount of water produced	Near Infrared Spectrometer
	Water Droplet Demo
Capture black and white images of water condensate/droplets produced during volatile analysis and hydrogen reduction processes.	Camera and Water Droplet Demo



# RESOLVE Mission Capabilities vs Lunar Strategic Knowledge Gaps (SKGs)



## Lunar Exploration Strategic Knowledge Gaps

RESOLVE

I. Understand the Lunar Resource Potential		
C/D	<b>Map and characteriize broadfeatures of polar cold traps</b>	
	A. Measure geotechnical characteristics of cold traps	
	Measure the size and shape distribution of grains in the lunar regolith	
	Measure bulk characteristics and geotechnical properties	
	B. Measure physiography and accessibility of cold traps	
	<b>Determine lateral and vertical distribution and extent of polar volatiles</b>	
	A. Measure concentration of water and other volatiles species within depth of 1-2 m	
	Extract subsurface sample down to 0.75 m (1.0 m goal)	
	Auger cuttings from depth of 0.5 m	
	Transfer samples 25 +/- 2 cubic centimeters in volume	
	Measure the relative abundance of the volatile constituents of a lunar subsurface regolith sample	
	Quantify the amount of water in the lunar regolith when water concentrations are between 0.5% to 8.0% by	
	B. Measure variability of water concentration on scales of 10's of meters	
	Determine the spatial distribution of hydrogen and hydrogen bearing volatiles with a min. horizontal	
	Measure the thermal and epithermal neutron fluxes corresponding to a 0.5 wt% water-equivalent layer at 1	
	Traverse the lunar surface with a minimum range of 1 km total point to point seperation. (Goal of 3 km)	
	C. Measure minearlogical, elemental, molecular, isotopic, make up of volatiles	
	Measure the reflected radiance to +/-25% between (at least) 1.8 and 3.3 microns for mineral and volatile	
	Perform visual and near infrared inspection of the augured cuttings.	
	Measure the isotope ratios of Deuterium to Hydrogen and Oxygen-16 to Oxygen-18	
	D. Measure physical nature of volatile species (e.g. pure concentrations, intergranular, globular)	
	E. Measure spatial and temporal distribution of OH and H2O at high latitudes	
	Measure spatial OH and H2O in the Near IR spectrum	
F/G	<b>Measure lunar ISRU production efficiency: Measure the efficiency of ISRU processes in the lunar</b>	
	Heat samples to 1175 K (902 C) to hydrogen reduction.	
	Measure amount of water produced	
	Capture black and white images of water condensate/droplets produced during volatile analysis and hydrogen reduction processes.	