Regolith Volatile Recovery at Simulated Lunar Environments

Julie Kleinhenz
NASA Glenn Research Center, Cleveland, Ohio, 44135

Gale Paulsen, Kris Zacny
Honeybee Robotics Spacecraft Mechanisms Corporation, Pasadena, Calif. 91103

Sherry Schmidt, and Dale Boucher
Deltion Innovations Ltd., Capreol, Ontario, Canada
Lunar Polar Volatiles

- Permanently shadowed craters at the lunar poles contain water, ~5 wt% according to LCROSS
- Interest in water for ISRU applications
- Desire to ‘ground truth’ water using surface prospecting – e.g. Resource Prospector & RESOLVE
- How to access subsurface water resources and accurately measure quantity
  - Excavation operations and exposure to lunar environment may affect the results
Volatile capture tests

• A series of ground based dirty thermal vacuum tests are being conducted to better understand the subsurface sampling operations
  – Sample removal and transfer
  – Volatiles loss during sampling operations
  – Concept of operations
  – Instrumentation

• This presentation is a progress report on volatiles capture results from these tests with lunar polar drill prototype hardware
  – Previous data published at this conference last year
  – New data in 2015 from two test series
    • Honeybee Robotics Auger w/ RESOLVE based sample crucibles
    • Deltion Destin Drill w/ customized sample tubes
Vacuum Facility

VF13 at NASA Glenn Research Center
- Dedicated ‘dirty’ vacuum chamber
- Volume of 6.35 m$^3$
- 3.66m tall by 1.5 m diameter
- Temperature controlled cold wall
  - 2 Semi circular sections, independently controlled
  - Liquid nitrogen cooled
- Tailored electrical and mechanical feed through
- Additional Liquid Nitrogen supply for experiment (soil bin)
- Pressures $O(10^{-6})$ Torr
Simulant Bed

- Simulant bed sized to accommodate drill tests
  - 1.2m (48in) tall, 0.278m (11in) diameter
  - Holds 100 kg of simulant
  - Height to accommodate full 1m drill
  - Diameter for multiple drill holes
  - Wrapped with LN$_2$ coolant lines
  - Three side ports for soil embedded thermocouples (15, type T)
  - LHT-3m and Chenobi, doped with moisture
Hardware Platform

• 2D translation table for positioning over soil bed
  – Remotely actuated stepper motors and chain drives
  – Drill is mounted to the trolley which can be moved in two dimensions
  – Multiple drill holes per test

• 4 cameras and LED lights for test monitoring at vacuum

• Drill, SCMs, cameras all mounted to translation table
Lunar Prospector Drill- Honeybee Robotics

- Developed by Honeybee Robotics, and based on the Mars Icebreaker drill, TRL 5/6
- 100cm long, 2.5cm diameter auger
  - 10cm sample section has wider flutes at high pitch to capture granular material
  - Progressive "Bite sampling" approach to drilling
    - Retains depth stratigraphy of the holes
    - Less material conveyed to surface, less chance of stuck bit
- Sample delivery mechanism
  - Deployed to surface as stabilizing foot
  - Fully contains the 10cm sample when auger retracted
  - Passive brush that rotates as auger spins past. Material brushed off auger and through funnel for collection
- Actuators: Percussion, deployment Z-stage, Drill Z-stage, Auger rotation
Lunar Prospector Drill - Honeybee Robotics

**Hammer System**
- 150 Watts
- 2-2.6 J/blow
- 2600 bpm
- Integrated in 8 different planetary drill systems

**Rotary System**
- Power: 150 Watt
- Rotation speed: 200 rpm
- Peak torque: 10 Nm

**Slipring**
- 4 channel
- Can support 1 RTD or 2 Thermocouples

**Z-Stage**
- Enables auger penetration to 1 m
- Pulley based
- Load from actuator current
- Max force: 500 N (any direction)

**Deployment Stage**
- Deploys and preloads drill against ground
- Pulley based
- Load from actuator current
- 40 cm stroke (depends on rover-ground clearance)
- Max force: 500 N (any direction)

**Sample Delivery**
1. Direct-to-Oven: Brush directly into a cup/oven

**Auger**
- Hollow: Enables wires for temp sensor to the bit
- Dual stage to enable sampling and auger cuttings to the surface.
- <25 mm diameter

**Bit**
- Tungsten Carbide
- Serrated cutters
- Embedded temperature sensor
Sample Capture Mechanisms (SCM)

- Capture 10cc of soil from the auger and seal at vacuum conditions to retain volatiles
- Solenoid actuated, spring driven mechanism with a knife edge-to-teflon seal, 100lbf clamp force
- Sealed 18ml crucibles easily removed for sample analysis
- 6 Sample Capture Mechanisms in each test for multiple samples.
Honeybee Video of operation: drill & transfer
DESTIN VDCU Drill – Deltion Innovations

- Evolution of autonomous DESTIN 1m drill
- TRL 6: operation at 10-6 torr, 100K
- Tools for augering to 50cm, capturing 1 m contiguous consolidated core, or capturing 1m contiguous unconsolidated core
- Sample stratigraphy retained in core samples (coloured CHENOBI testing)
- Volatile retention in core samples
- Low power (<50Watts, including heaters for 1m sample, <40Watts to auger)
- Low thrust (nominal 100N)
- Core samples in frozen simulant at moisture concentrations from 0-5%, augering in 0-100%
- Bit temperature sensor in auger
Deltion Sample capture

Transfer Tube

- Ball valve seal
- Teflon tubes:
  - 2ft long, 1in diameter
  - Folded w/ grease, and clamped with hosecock style clamp
- Tested on a leak checker to prove concept

Tool capture

- At the end of last drill hole, tool pressed into sheath to seal
Video of Transfer
<table>
<thead>
<tr>
<th>Test</th>
<th>Start Date</th>
<th>Test objective/ description</th>
<th>Soil Type</th>
<th>Soil Moisture</th>
<th>Lowest Vacuum, Torr</th>
<th>Shroud Temperature, °C</th>
<th>Avg soil temp (low), °C</th>
<th>Operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Honeybee NIRVSS 1</td>
<td>3/5/2015</td>
<td>Volatiles loss and sensitivity of NIRVSS. 5 sample capture crucibles</td>
<td>LHT</td>
<td>Stratified: room dry 5% room dry</td>
<td>5.E-06</td>
<td>-53</td>
<td>-80</td>
<td>5 holes to 40cm, 5 samples from 40cm</td>
</tr>
<tr>
<td>Honeybee NIRVSS 2</td>
<td>3/15/2015</td>
<td>Volatiles loss and sensitivity of NIRVSS. 5 sample capture crucibles</td>
<td>LHT</td>
<td>Stratified: 0.5% 5% 0.5%</td>
<td>2.E-06</td>
<td>-175</td>
<td>-100</td>
<td>5 holes to 40cm, 5 samples from 40cm</td>
</tr>
<tr>
<td>Deltion 1, auger</td>
<td>6/22/2015</td>
<td>Auger w/telflon capture tubes x2 and tool capture</td>
<td>Chenobi</td>
<td>5%</td>
<td>1.E-06</td>
<td>-175</td>
<td>-115</td>
<td>3 holes to 50cm, 3 samples</td>
</tr>
<tr>
<td>Deltion 2, Core</td>
<td>6/29/2015</td>
<td>Core auger w/telflon capture tubes x2 and tool capture</td>
<td>Chenobi</td>
<td>reuse 5%</td>
<td>1.E-06</td>
<td>-175</td>
<td>-115</td>
<td>2 holes to 85cm, 2 samples</td>
</tr>
<tr>
<td>Deltion 3, Push</td>
<td>7/1/2015</td>
<td>Push tube w/telflon capture tubes x2 and tool capture</td>
<td>Chenobi</td>
<td>2%</td>
<td>1.E-06</td>
<td>-175</td>
<td>-112</td>
<td>1 hole to 25cm, 1 sample</td>
</tr>
<tr>
<td>Deltion 4, Core</td>
<td>7/8/2015</td>
<td>Core auger w/telflon capture tubes x2, and tool capture</td>
<td>Chenobi</td>
<td>reuse 2%</td>
<td>2.E-06</td>
<td>-175</td>
<td>-111</td>
<td>2 holes to 75+ cm 2 samples</td>
</tr>
</tbody>
</table>
# Honeybee Test Matrix

## DRILL TUBE 1
(Dry: 0.1%, Wet: 5%, Dry: 0.1%, )

<table>
<thead>
<tr>
<th>Sample 1 – SCM 2, Crucible 2</th>
<th>Shroud Temp</th>
<th>Crucible Temp</th>
<th>Time to Seal</th>
<th>Bit Temp, C</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 50 C</td>
<td>Ambient</td>
<td>Fast as possible</td>
<td>-45</td>
<td></td>
</tr>
<tr>
<td>Sample 2 – SCM 4, Crucible 4</td>
<td>- 50 C</td>
<td>Ambient</td>
<td>Fast as possible</td>
<td>-45</td>
</tr>
<tr>
<td>Sample 3 – SCM 6, Crucible 6</td>
<td>- 50 C</td>
<td>Ambient</td>
<td>Fast as possible</td>
<td>-47</td>
</tr>
<tr>
<td>Sample 4 – SCM 3, Crucible 3</td>
<td>- 50 C</td>
<td>Ambient</td>
<td>3 minutes after transfer</td>
<td>48</td>
</tr>
<tr>
<td>Sample 5 – SCM 5, Crucible 5</td>
<td>- 50 C</td>
<td>Ambient</td>
<td>3 minutes after transfer</td>
<td>46</td>
</tr>
</tbody>
</table>

## DRILL TUBE 2
(Dry: 0.5%, Wet: 5%, Dry: 0.5%, )

<table>
<thead>
<tr>
<th>Sample 1 – SCM 2, Crucible 8</th>
<th>Shroud Temp</th>
<th>Crucible Temp</th>
<th>Time to Seal</th>
<th>Bit Temp, C</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 180 C</td>
<td>10 C</td>
<td>3 minutes after transfer</td>
<td>-68</td>
<td></td>
</tr>
<tr>
<td>Sample 2 – SCM 4, Crucible 10</td>
<td>- 180 C</td>
<td>10 C</td>
<td>3 minutes after transfer</td>
<td>-66</td>
</tr>
<tr>
<td>Sample 3 – SCM 6, Crucible 12</td>
<td>- 180 C</td>
<td>10 C</td>
<td>3 minutes after transfer</td>
<td>-64</td>
</tr>
<tr>
<td>Sample 4 – SCM 3, Crucible 9</td>
<td>- 180 C</td>
<td>10 C</td>
<td>3 minutes after transfer</td>
<td>-64</td>
</tr>
<tr>
<td>Sample 5 – SCM 5, Crucible 11</td>
<td>- 180 C</td>
<td>Ambient</td>
<td>3 minutes after transfer</td>
<td>-64</td>
</tr>
</tbody>
</table>
Test 1 – Soil Bin profile

Note: Lower dry layer was not sampled to full depth (yet). Coring method does not work with dry soil, so ~60cm is as far as I can reach without dumping the bin.
Test 2 – Soil Bin profile

Note: Lower dry layer was not sampled to full depth (yet). Coring method does not work with dry soil, so ~60cm is as far as I can reach without dumping the bin.
Results from Honeybee sample capture

2014 test results, previously presented
- Only well sealed sample captures are shown.
- Variables: Crucible exposure time, crucible temperature, ambient temperature

Results from HB Auger capture

Moisture losses were in the same range as previous tests, but do not line up with sublimation curve.

Results from Honeybee capture

Moisture losses in the same range as previous tests, but do not line up with sublimation curve. Potential variables influence:

- Stratified soil bin: step change in moisture content may have resulted in more cross contamination during drilling
- The holes were drilled using the bite approach, while the 2014 samples were straight drills.
- Potential residual dry sample material at brush spout
- The brush was exposed
- The NIRVSS lamp was on intermittently while sample was removed.
- Overall chamber pressure was lower than in previous tests
## Deltion Test Matrix

### DRILL TUBE 1, 5%

<table>
<thead>
<tr>
<th>Sample capture</th>
<th>Depth</th>
<th>Bit Temp at depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auger, Sample 1</td>
<td>Transfer Tube</td>
<td>50 cm</td>
</tr>
<tr>
<td>Auger, Sample 2</td>
<td>Transfer Tube</td>
<td>50 cm</td>
</tr>
<tr>
<td>Auger, Sample 3</td>
<td>Tool Capture</td>
<td>50 cm</td>
</tr>
</tbody>
</table>

### DRILL TUBE 1, 5%, reuse

<table>
<thead>
<tr>
<th>Sample capture</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coring Auger, Sample 1</td>
<td>Transfer Tube</td>
</tr>
<tr>
<td>Coring Auger, Sample 2</td>
<td>Tool Capture</td>
</tr>
</tbody>
</table>

### DRILL TUBE 2, 2%

<table>
<thead>
<tr>
<th>Sample capture</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Push Tube, sample 1</td>
<td>Tool Capture</td>
</tr>
</tbody>
</table>

### DRILL TUBE 2, 2% reuse

<table>
<thead>
<tr>
<th>Sample capture</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coring Auger, Sample 1</td>
<td>Transfer Tube</td>
</tr>
<tr>
<td>Coring Auger, Sample 2</td>
<td>Tool Capture</td>
</tr>
</tbody>
</table>
Results from Deltion Capture

- Results indicate water content over entire depth of hole. Only one sample was analyzed for stratification.
- The tool capture method retained more moisture than the transfer tubes.
  - Final sample (4 core tool capture) reused a capture mechanism not intended for reuse.
- The transfer process was not optimized for volatiles retention.

<table>
<thead>
<tr>
<th>Test, tool</th>
<th>Notes</th>
<th>Sample container</th>
<th>Soil prep</th>
<th>Wet soil mass, g</th>
<th>Dry Soil mass, g</th>
<th>Water mass</th>
<th>Water %, dry basis</th>
<th>% of available water lost</th>
<th>Drill Depth, cm</th>
<th>Bit temp, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, auger</td>
<td>Transfer tube</td>
<td>5%</td>
<td>0.7</td>
<td>0.7</td>
<td>0.0</td>
<td>0.00%</td>
<td>100.0%</td>
<td>50</td>
<td>-72</td>
<td></td>
</tr>
<tr>
<td>1, auger</td>
<td>Transfer tube</td>
<td>5%</td>
<td>3.5</td>
<td>3.5</td>
<td>0.0</td>
<td>0.00%</td>
<td>100.0%</td>
<td>50</td>
<td>-85</td>
<td></td>
</tr>
<tr>
<td>1, auger</td>
<td>Tool capture</td>
<td>5%</td>
<td>14.8</td>
<td>14.7</td>
<td>0.1</td>
<td>0.68%</td>
<td>86.4%</td>
<td>50</td>
<td>-90</td>
<td></td>
</tr>
<tr>
<td>2, core</td>
<td>Transfer tube</td>
<td>5%</td>
<td>88.2</td>
<td>85.7</td>
<td>2.5</td>
<td>2.89%</td>
<td>42.1%</td>
<td>85</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>2, core</td>
<td>Tool capture</td>
<td>5%</td>
<td>118.4</td>
<td>114.0</td>
<td>4.4</td>
<td>3.84%</td>
<td>23.3%</td>
<td>85</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>3, Push tube</td>
<td>Tool capture</td>
<td>2%</td>
<td>65.7</td>
<td>65.6</td>
<td>0.1</td>
<td>0.22%</td>
<td>88.9%</td>
<td>25</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>4, core</td>
<td>Transfer tube</td>
<td>2%</td>
<td>115.1</td>
<td>114.2</td>
<td>0.9</td>
<td>0.83%</td>
<td>58.7%</td>
<td>75</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>4, core</td>
<td>SUMMED Tool capture</td>
<td>2%</td>
<td>147.0</td>
<td>145.4</td>
<td>1.7</td>
<td>1.14%</td>
<td>42.8%</td>
<td>83</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>4, core</td>
<td>bit end</td>
<td>(This sample was removed in sections to look at moisture distribution)</td>
<td>2%</td>
<td>20.0</td>
<td>19.9</td>
<td>0.1</td>
<td>0.46%</td>
<td>76.9%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4, core</td>
<td>shaft 1</td>
<td>2%</td>
<td>22.2</td>
<td>21.9</td>
<td>0.3</td>
<td>1.42%</td>
<td>28.9%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4, core</td>
<td>shaft 2</td>
<td>2%</td>
<td>54.8</td>
<td>54.0</td>
<td>0.8</td>
<td>1.50%</td>
<td>25.0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4, core</td>
<td>Bed surface</td>
<td>2%</td>
<td>50.0</td>
<td>49.6</td>
<td>0.5</td>
<td>0.91%</td>
<td>54.5%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Results from Deltion Capture

- **Auger tool:** Not designed for sample capture. Little sample <15g captured from auger flights. Samples were dry, but sample tube seal was poor.
- **Push Tube:** One sample captured 65g. Logistical issues of sample transfer resulted in long exposure/possible poor seal. Sample lost 88% of its water. 
- **Coring Auger:** 4 samples averaging 115 g captured per hole. Water retention in same range as the Honeybee capture tests

<table>
<thead>
<tr>
<th>Test, tool</th>
<th>Notes</th>
<th>Sample container</th>
<th>Soil prep</th>
<th>Wet soil mass, g</th>
<th>Dry Soil mass, g</th>
<th>Water mass</th>
<th>Water %, dry basis</th>
<th>% of available water lost</th>
<th>Drill Depth, cm</th>
<th>Bit temp, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, auger</td>
<td>Transfer tube</td>
<td>5%</td>
<td>0.7</td>
<td>0.7</td>
<td>0.0</td>
<td>0.00%</td>
<td>100.0%</td>
<td></td>
<td>50</td>
<td>-72</td>
</tr>
<tr>
<td>1, auger</td>
<td>Transfer tube</td>
<td>5%</td>
<td>3.5</td>
<td>3.5</td>
<td>0.0</td>
<td>0.00%</td>
<td>100.0%</td>
<td></td>
<td>50</td>
<td>-85</td>
</tr>
<tr>
<td>1, auger</td>
<td>Tool capture</td>
<td>5%</td>
<td>14.8</td>
<td>14.7</td>
<td>0.1</td>
<td>0.68%</td>
<td>86.4%</td>
<td></td>
<td>50</td>
<td>-90</td>
</tr>
<tr>
<td>2, core</td>
<td>Transfer tube</td>
<td>5%</td>
<td>88.2</td>
<td>85.7</td>
<td>2.5</td>
<td>2.89%</td>
<td>42.1%</td>
<td></td>
<td>85</td>
<td>NA</td>
</tr>
<tr>
<td>2, core</td>
<td>Tool capture</td>
<td>5%</td>
<td>118.4</td>
<td>114.0</td>
<td>4.4</td>
<td>3.84%</td>
<td>23.3%</td>
<td></td>
<td>85</td>
<td>NA</td>
</tr>
<tr>
<td>3, Push tube</td>
<td>Tool capture</td>
<td>2%</td>
<td>65.7</td>
<td>65.6</td>
<td>0.1</td>
<td>0.22%</td>
<td>88.9%</td>
<td></td>
<td>25</td>
<td>NA</td>
</tr>
<tr>
<td>4, core</td>
<td>Transfer tube</td>
<td>2%</td>
<td>115.1</td>
<td>114.2</td>
<td>0.9</td>
<td>0.83%</td>
<td>58.7%</td>
<td></td>
<td>75</td>
<td>NA</td>
</tr>
<tr>
<td>4, core</td>
<td>SUMMED</td>
<td>Tool capture</td>
<td>2%</td>
<td>147.0</td>
<td>145.4</td>
<td>1.7</td>
<td>1.14%</td>
<td>42.8%</td>
<td>83</td>
<td>NA</td>
</tr>
<tr>
<td>4, core</td>
<td>bit end</td>
<td>(This sample was removed in sections to look at moisture distribution)</td>
<td>2%</td>
<td>20.0</td>
<td>19.9</td>
<td>0.1</td>
<td>0.46%</td>
<td>76.9%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4, core</td>
<td>shaft 1</td>
<td>(This sample was removed in sections to look at moisture distribution)</td>
<td>2%</td>
<td>22.2</td>
<td>21.9</td>
<td>0.3</td>
<td>1.42%</td>
<td>28.9%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4, core</td>
<td>shaft 2</td>
<td>(This sample was removed in sections to look at moisture distribution)</td>
<td>2%</td>
<td>54.8</td>
<td>54.0</td>
<td>0.8</td>
<td>1.50%</td>
<td>25.0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4, core</td>
<td>Bed surface</td>
<td>(This sample was removed in sections to look at moisture distribution)</td>
<td>2%</td>
<td>50.0</td>
<td>49.6</td>
<td>0.5</td>
<td>0.91%</td>
<td>54.5%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Post Mortem

• Despite reusing each simulant bed for multiple tests, the moisture content at the end showed little desiccation.
  – Conops: The bed was exposed to room air while still chilled, frost build up may have added moisture to bin to counter losses.
Results with Core Capture

- Core results
- Significantly more sample mass encompassing a broader depth, so average of drier surface layer and wetter soil at depth

![Graph showing water lost and sublimation rate vs. ambient temperature. The graph includes data points labeled with Crucible # and indicates the best seal.](image)
Sectioned sample

- Exposed end of core auger shows water loss
- The center of the sample retained moisture more in line with predicted losses
Conclusions

• Previous data showed the volatile loss from augured samples was primarily a function of ambient environment conditions (exposure)

• Both of the new sampling results included new variables and configurations, so the data does not fall in line with previous results

Auger sampling method
• Stratified moisture content in soil bin, potential cross contamination from dry layers

Core samples
• Transfer tubes did not seal well, limiting data set
• In tool sample capture retains more moisture overall
• Non-uniform con-ops, different soil exposures
• Larger sample sizes over broader depth so dry surface material in core combined with wet center: Retention of stratification not shown here

• Continued analysis of this data with new upcoming tests in 2016