Field Testing of K10 with HYDRA at NASA Ames Research Center

R. Elphic\(^1\), L. Kobayashi\(^2\), M. Allan\(^2\), M. Bualat\(^2\), M. Deans\(^2\), T. Fong\(^2\), S. Y. Lee\(^2\), V. To\(^2\), and H. Utz\(^2\)

\(^1\)Planetary Systems Branch, NASA Ames Research Center, Moffett Field, CA 94035; PH: 650-604-4164; e-mail: Richard.c.elphic@nasa.gov
\(^2\)Intelligent Robotics Group, NASA Ames Research Center, Moffett Field, CA 94035

ABSTRACT

High resolution hydrogen surface mapping is essential for locating and characterizing water ice and other hydrogenous volatile deposits in permanently shadowed lunar craters. This is especially important for potential in-situ resource utilization. Although orbital remote sensing can provide much information, prospecting for near-subsurface resources can only be performed directly on the surface. The small HYDRA neutron spectrometer has been successfully integrated onto the K10 Black planetary rover, operated by the Intelligent Robotics Group at NASA Ames Research Center [1,2]. The system was used to assess hydrogen content in an initial set of field tests at Ames. During these tests, we successfully detected and mapped targets of various hydrogen contents and burial depths.

TEST OBJECTIVES

The objectives of the exercise were as follows:

- Integrate and operate the HYDRA neutron spectrometer with the K10 Black rover.
- Acquire HYDRA data as the rover navigates a grid of GPS waypoints chosen without prior knowledge of the target locations.
- Detect and localize near-surface enhanced hydrogen deposits within the rover test area.

TEST LOCATION AND SETUP

The K10/HYDRA rover tests were carried out from Sept. 18 – 20, 2007 at an unvegetated pad of fill dirt, north of building TA27B at the NASA Ames Research Center. The area is shown in Figure 1. The extent of the test area was approximately 50 meters in the north-south direction, and 20 meters in the east-west direction. Within this area holes were excavated. One set of targets consisted of 3x3 foot polyethylene slabs (each 0.5 in thick, stacked 8 deep for an overall thickness of ~10 cm), buried at depths of 0, 5, 15 and 30 cm. Another set of targets consisted of 4x4 ft, 2x2 ft, and 1x1 ft stacks of cut 0.5-inch thick drywall (gypsum), each stacked 12 deep for an overall thickness of 15 cm. Finally, some excavations were simply back-filled with the excavated material to act as decoys for the test. The locations of the polyethylene and gypsum targets were known only to three personnel involved in the exercise, in order to provide a single-blind test.
A Californium-252 neutron source (activity of ~2x10^6 neutrons/s) was used to interrogate the soil beneath the rover. The source was co-located with the HYDRA instrument, to provide a fixed geometry and to minimize the effects of variations in soil-to-source distance (approx. 15 cm). Figure 2 shows HYDRA and the source mounted on the front of K10 Black. When the energetic neutrons from the source interact with hydrogenous materials, HYDRA measures an enhanced backscatter “albedo” flux of thermal and epithermal neutrons as the robot traverses the site.

Test site preparations also included establishing power and network connections for base operations, and establishing and properly posting a radiation safety perimeter around the area where the rover operations will involve use of the neutron source. GPS locations within the test area were also determined prior to testing.

TEST EXECUTION

Once all test area preparations were completed, test execution was divided into 3 phases:

(1) Phase 0, Calibration: K10/HYDRA was traversed across the
known locations of three targets at four speeds: 5, 10, 20, and 40 cm/s. HYDRA data were reviewed to then establish the speeds at which the next test phases would be carried out.

(2) Phase I: K10/HYDRA was traversed across the test area by means of a series of predetermined GPS waypoints that were uploaded to the robot. This plan resulted in a series of parallel line transects, separated by approximately 1 m in the east-west direction, intended to provide coarse coverage of the test area.

(3) Phase II: Interesting features detected in the Phase I transect survey are revisited by K10, and a finer grid of spatial sampling is obtained by executing a series of square spirals from the center point.

REAL TIME TEST MONITORING

Figure 3 shows a screenshot of the NASA Ames Viz 3D user interface, which was used to monitor K10 test progress, and identify targets of interest for Phase II testing. This view shows the results of a series of north-south transects carried out as part of Phase II testing. Viz monitors telemetry from the rover and generates data maps of the surveyed site in real time. Pose estimates from the robot are used to continually update a height field that represents the surface geometry. The rover's sensor data is binned to create 2D intensity maps that can be projected onto the terrain. Figure 3 shows HeSn counts, binned into 1m cells. A strong signal (red square) from the polyethylene calibration target can be seen in the foreground.

TEST RESULTS

Phase 0, Calibration: The calibration phase was performed on September 18, 2007. The left panel of Figure 4 shows K10/HYDRA during one of the traverses over the three calibration targets. The right panel shows the HYDRA HeSn detector response when passing over the polyethylene calibration target. Based on the data collected during these traverses, it was determined that the rover speed should be 10 cm/s for the Phase I transect survey. The 5 cm/s speed provided excellent resolution but required too much time to complete the survey; the 20 cm/s and 40 cm/s speeds created slight offsets in position and did not satisfactorily resolve the extent of the smaller targets.

The calibration phase also revealed the surprisingly high hydrogen content of the supposedly dry soil of the test area. Clay minerals make up a substantial fraction of the dirt in this area; results of geochemical analysis are reported later.

Phase 1: The transect survey was carried out by assembling a series of GPS waypoints that covered the test area with 1-meter separations between transects. The robot proceeded through the series of waypoints at 10 cm/s.
Figure 4. (Left) Calibration Phase traverse. Note the exposed polyethylene in the foreground. Beyond this is a target of gypsum buried 15 cm deep. The rover is situated above a gypsum target at the surface. (Right) Comparison of sample spacing for the four traverse speeds. Note offsets due to lags in position updates at higher speeds.

Figure 5a shows a map of the rover traverse for Phase I in the top panel. Because of the way the rover executed turns and headed toward subsequent waypoints, the transect spacing was sometimes greater than 1 meter. Considerable information was obtained in the Phase I survey, as can be seen in Figure 5b. These are maps of binned HeSn (thermal+epithermal) and HeCd (epithermal only) count rates from HYDRA. The bin size is 50x50 cm. We have truncated the

K10 Traverse Path

Figure 5a. K10 traverse path for the Phase I survey. The transect separations were planned to be 1 m apart.
color scale at 250 counts/s for the HeSn map, in order to bring out the detail seen across the test area. Note the HeSn highs at the polyethylene calibration target at (720, 66) m, and at (754, 72) m. Note also the HeSn low at (725, 66) m, also seen in the HeCd map. This low corresponds to a deposit of dried Monterey beach sand, which has far less hydrogen than the surrounding soil. Its mean mass density is also less than the fill soil, permitting the neutrons to travel farther before scattering. Finally, we note that the eastern third of the test area consists of a dark-toned material. Geochemical analysis of the soils revealed that this material contains more Fe$_2$O$_3$ and TiO$_2$ than the lighter-toned material. This dark-toned soil can be seen in Figure 6, showing K10/HYDRA near (730, 80) m near (730, 80) m in the eastern part of the test area. This material is richer in Fe$_2$O$_3$ and TiO$_2$ than the lighter-toned material to the west.
Phase II: The next step was to carry out a more detailed investigation of selected features identified in the Phase I survey, as shown in Figure 7. We chose to include the calibration features in this study as a way of testing K10’s ability to perform high spatial resolution investigations of small features. Also included were some of the interesting features seen elsewhere in the test area. The rover was directed to move to the center of designated feature locations, and it then carried out a rectangular spiral search pattern around the target. In this way a higher sample density was obtained, permitting the delineation of the spatial extent of the feature.

Figure 7 shows that the Phase II traverses are dominated by spiral sampling patterns centered on the points of interest. The HeSn detector clearly detects and places limits on the hot spot of the polyethylene calibration target at (721, 66) m. To its right the dry sand target and the exposed gypsum targets show up as lower count rate areas. On the right, at (754.5, 72.5) m, a second hotspot is clearly revealed. This was a polyethylene target buried under 5 cm of soil.

We also carried out a series of north-south and east-west transects across the larger area of the northwest corner of the test area, as shown in Figure 8. The K10 traverse path is superimposed on the HeSn count rate map. The hot spot at (754.5, 72.5) m, clearly seen in Figures 4 and 6, is not seen here. The reason is that the rover just missed the location on each
transect. This result shows that the effective radial range for detection, given the K10/HYDRA mounting geometry shown in Figures 2 and 6, is no more than 50 cm. Both the source and the instrument are approximately 15 cm from the soil surface.

**All Phase I and II Data:** Figure 9 shows all Phase I and II data summed up to make as complete an HeSn map as possible. The top left panel shows all K10 traverses and inspections, while the top right panel shows the log of the number of HYDRA samples obtained in each 50x50 cm bin (black denotes no samples). The lower left and right panels show the mean count rate for the HeSn (thermal + epithermal) and HeCd (epithermal only) detectors, respectively. The two hotspots in HeSn are clearly seen, associated with the polyethylene calibration target and the “discovered” feature of interest at (754.5, 72.5) m. Count rate lows include the sand pit at (725, 66) m, the gypsum target at (730, 66) m, and a feature near (740, 66) m. Interestingly, no hint of an epithermal enhancement is seen for the latter feature.

Figure 10 shows the HeSn map geolocated on a GoogleEarth satellite image of the test area. Note the correspondence between test area albedo and HeSn count rate – there is a clear relationship between decreased thermal neutron flux and the dark-toned fill materials present at the test site. We discuss these features below.

**DISCUSSION**

The test met all objectives. Complete success was not achieved due to the high hydrogen content of the soils in which the targets were buried. These soils were poor analogs for the Moon, but reasonable as an analog for some Martian materials containing phyllosilicates or evaporite sequences.
An XRF assessment of soil composition is shown in Table 1. The light- and dark-toned soils were found to have roughly the same total water content. The dark-toned soils clearly have higher Fe$_2$O$_3$ and TiO$_2$ content, and so the reason for reduced thermal neutron flux becomes apparent. Iron has a large cross section for thermal neutron capture, 2.59 barn, and titanium is even larger, 6.11 barn (1 barn=$10^{-24}$ cm$^2$). The reduced thermal flux reflects the increased capture of thermal neutrons in the higher-Fe and Ti soil. Such mafic soil compositions are not found in the lunar highlands near the poles; we expect the thermal neutrons to be affected primarily by the presence of hydrogen. However, the thermal and epithermal neutron behavior seen in these tests, using an external source, is different from what we expect when galactic cosmic rays generate the neutrons within the soil [3]. In this case, which obtains on the Moon, the neutron leakage flux behaves as shown in Figure 11.

![Figure 10. Transect survey results displayed in Google Earth. The colored squares represent count rates detected by HYDRA’s He-Sn detector from low (dark blue) to high (red). The dark soil in the eastern (lower) part of the survey area appears to contain less hydrogen than the rest of the area.](image)

<table>
<thead>
<tr>
<th>Wt%</th>
<th>Light-toned Material</th>
<th>Dark-toned Material</th>
<th>Clean Beach Sand</th>
<th>Polyethylene (C$_2$H$_2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>66.0</td>
<td>58.0</td>
<td>83.8</td>
<td>-</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>0.66</td>
<td>1.06</td>
<td>0.06</td>
<td>-</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>14.2</td>
<td>13.8</td>
<td>9.08</td>
<td>-</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>5.53</td>
<td>7.92</td>
<td>0.48</td>
<td>-</td>
</tr>
<tr>
<td>MnO</td>
<td>0.06</td>
<td>0.11</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td>MgO</td>
<td>1.69</td>
<td>3.37</td>
<td>0.15</td>
<td>-</td>
</tr>
<tr>
<td>CaO</td>
<td>2.39</td>
<td>5.18</td>
<td>1.03</td>
<td>-</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>2.02</td>
<td>2.17</td>
<td>2.03</td>
<td>-</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>1.72</td>
<td>1.47</td>
<td>3.08</td>
<td>-</td>
</tr>
<tr>
<td>Moisture</td>
<td>4.2</td>
<td>3.6</td>
<td>0.1</td>
<td>-</td>
</tr>
<tr>
<td>LOI - CO$_2$</td>
<td>5.7</td>
<td>6.5</td>
<td>0.4</td>
<td>-</td>
</tr>
<tr>
<td>TOTAL H$_2$O</td>
<td>9.9</td>
<td>10.1</td>
<td>0.5</td>
<td>“100”</td>
</tr>
</tbody>
</table>
Here we show the thermal vs. epithermal fluxes as a function of burial depth (blue contours) and water ice abundance (orange contours). Note that having a pair of measurements, thermal and epithermal flux, permits an estimate not only of the water ice abundance but also of its burial depth. For example, 3 wt% icy soil at 10 g/cm² burial depth have a higher thermal flux, but a lower epithermal flux than dry (0.1 wt%) soil at the same depth. Thus the neutron spectrometer measurements from a rover provide at all times an important prospecting tool: an assessment of “ore grade” (abundance) and “ease of access” (burial depth). Promising deposits can be readily identified with this passive interrogation technique. No external source is required.

ACKNOWLEDGMENTS

This work was supported by the NASA Exploration Technology Development Program, the Mars Instrument Development Program, and the Mars Fundamental Research Program.

REFERENCES