ROCKET DISPERSED INSTRUMENTS: A MISSION ARCHITECTURE FOR EXPLORING LUNAR POLAR HYDROGEN. I. Garrick-Bethell[1], J. J. West[2], D. J. Lawrence[3], and R. C. Elphic[3], [1]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA, 02139, iang@mit.edu, [2]The Charles Stark Draper Laboratory, 555 Technology Square, Cambridge, MA 02139, jwest@draper.com, [3]Los Alamos National Laboratory, Los Alamos, NM, 87545.

Introduction: The distribution of lunar hydrogen is not known at a resolution better than 30-45 km [1]. If the neutron spectrometer on the 2008 Lunar Reconnaissance Orbiter (LRO) achieves its maximum potential, the resulting hydrogen abundance map will have a resolution of ~10 km at the poles (Fig. 1) [2]. When combined with other LRO data, such as crater morphology, area of permanent shade, and temperature, substantial improvements will be made in understanding the distribution and abundance of polar volatiles. However, even with these orbital measurements, significant uncertainties will likely remain regarding the form of the hydrogen (e.g. water, solar wind hydrogen, or other) and its fine scale spatial distribution (100-2000 m). Without such knowledge it is possible that a future human mission may encounter hydrogen in a form not amenable to utilization, or that the landing site chosen is too distant from significant quantities of hydrogen. Therefore, it will be essential to perform in situ mapping and characterization of polar hydrogen before any human mission that wishes to exploit or study it in detail. After an initial site characterization, our proposed architecture can be used indefinitely for follow up mapping studies by humans on the surface.

RDI concept: Our new robotic mission concept is known as Rocket Dispersed Instruments (RDI) and was originally presented in reference [3]. The concept was also presented to Goddard Space Flight Center in 2005. Here we demonstrate how this mission architecture has lower risk and cost than other robotic mission architectures.

Example mission. Our example mission calls for studying hydrogen in the permanently shadowed 10-km-radius Shackleton crater on the lunar south pole. Shackleton crarter is a destination that NASA has tentatively selected for human missions, and we assume that LRO shows at least a hint of hydrogen within several kilometers of the proposed human landing site (Fig. 1).

A fixed lander is first delivered to the rim of Shackleton crater. From the lander, 10-20 rocket powered probes of ~8 kg each are launched into the crater interior, achieving ranges from 0.1 to 10 km. These missile-shaped probes make a hard landing at ~125 m/s and are instrumented to characterize the subsurface hydrogen abundance within a meter of the impact site, within ~24 hours.

The probes transmit their data via an omnidirectional antenna directly to the Earth, or to the launcher, which relays the data to Earth. Since the probes have very short lifetime requirements, and the lunar soil is a poor thermal conductor, the low soil temperature (40-100° K) is not a significant challenge. The probes can be accurately targeted to obtain multiple measurements within 100 m, meeting the requirement to map out concentrated areas for further scientific study and potential resource utilization.

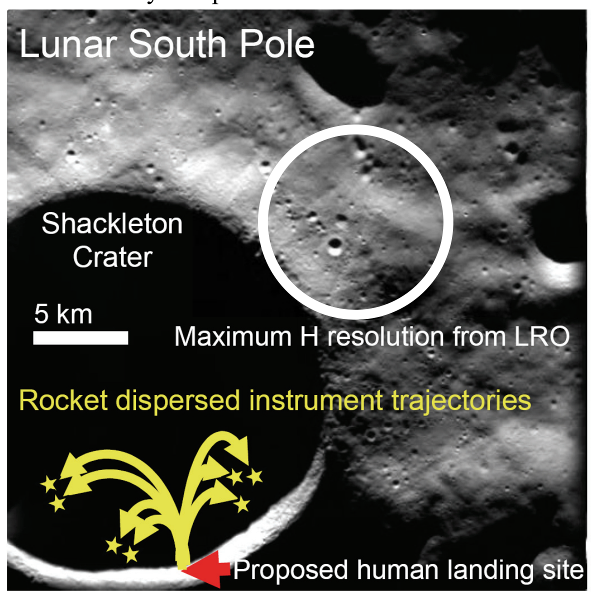

Figure 1: The RDI architecture at Shackleton crater.

Payload: At least two instruments are required on every probe. The first is a neutron spectrometer to determine the quantity of hydrogen 1-2 meters below the probe, and compare count rates to those derived from orbit. Los Alamos National Laboratory has built and successfully tested such instruments up to 1800g in earth-based penetrator tests. The entire spectrometer has a mass of 517 g, draws 2.25 W, and can be packaged in a variety of configurations. The second instrument acquires a small soil sample, heats it, and detects evolved gases to test for water. A similar instrument flew on the unsuccessful Deep Space 2 (DS2) Mars penetrators and could be used again here.

Communications: Line of sight radio communication between the probe and the launcher on a high rim is not difficult, since at a 10 km range (Shackleton's radius) only ~35 meters of elevation is required for horizon visibility. The lunar regolith is rather transparent to radio waves, such that if the unit lands in a shallow, relatively dry crater, its transmissions will penetrate a few meters with only modest attenuation. In addition, high-resolution topography data from LRO can be used to avoid deep craters if the risk is deemed sufficiently high. Finally, some areas of Shackleton may have direct line of sight communication with Earth. The data rates for neutron spectrometers and water detectors are very low.

Power: Peak power requirements are driven mainly by the propulsion system, which can at times require 23 W. A low continuous draw of current is also required for keeping the probe warm after impact. Primary lithium sulfur dioxide batteries can provide the requisite power with a mass of 240 g.

Advantages over rovers: There is substantial technical risk and cost associated with operating a rover in a cryogenic environment in complete darkness. The lack of light makes driving difficult, and reaching a number of distant locations comparable to that achieved by the RDI concept would require a high total mission lifetime and cost. In addition, unless a communication relay is employed at the rim of the crater or elsewhere, communications would be limited to locations where the Earth is in direct view. If nuclear power is used the cost of the rover could be on the scale of the nuclear powered Mars Science Laboratory rover, approximately $1.5 billion. Lastly, a precursor rover mission may be overkill, since human campaigns will eventually perform more thorough investigations using drills and excavators.

Advantages over orbit-deployed penetrators: Previous studies have proposed launching instrumented penetrators from an orbiting spacecraft. This architecture has never been successfully realized. Significant technical hurdles include very high impact velocities, dynamics and control, and difficulty in high accuracy targeting. Japan recently canceled a similar mission due to technical problems. In contrast, NASA knows how to deliver a fixed lander to the Moon and how to accurately launch projectiles from the ground, as required for RDI. The impact velocities of the 10 km range RDI probes are significantly lower than those of the DS2 and Japanese penetrators, and can be reduced arbitrarily without technical constraint.

Advantages over "hoppers": A heavily instrumented hopping lander has been proposed to jump between multiple locations within a permanently shadowed crater. This architecture suffers large risk due to repetitive soft-landings, which has always been the most risky part of robotic surface exploration. In addition, the vehicle would be unlikely to cover as wide an area as the RDI architecture, and suffers from the same power and communication problems as a rover. A hopper would also swamp the landing area with contaminating hydrogen compounds if hydrazine propellant were used.

Other advantages: *Penetration*. The kinetic energy of the RDI projectiles allows for a modest amount of penetration into the regolith. This can facilitate access to subsurface soil.

Human landing site characterization. A fixed lander at the rim of Shackleton crater could provide high-resolution images of the area during landing. While LRO image and topography data will probably be sufficient to plan a human landing, the data provided by a lander would be supportive and useful.

Continuous use by humans. If the launcher is built with sufficient modularity and robustness, humans may eventually visit and reload it with more projectiles to study new areas of Shackleton without the need to rove or walk to distant locations.

RDI cost: Total cost estimates at this level of maturity and for this type of mission are difficult. Nonetheless, we estimate that 12 probes and a lander will cost $480 million, including launch. This estimate is based on the cost of past missions, including DS2.

Work to date: We have invested several hundred hours in trade studies, design details, and mass estimates. The propulsion, communication, and power subsystems have matured to selection of COTS components. One of the most subtle, yet significant challenges of the RDI concept is assuring that the probe lands with its nose pointing into the regolith. Since there is no atmospheric drag to reorient the probe during flight, the probe will impact the surface with whatever orientation it had when launched. We have identified two realizable techniques to solve this problem. We note that Draper Laboratory has extensive experience with impact hardened electronics (e.g. in artillery shells with accelerations over 10,000g), novel guidance and control problems, and microelectromechanical systems.

Conclusion and recommendation: The RDI architecture can provide fine scale polar hydrogen data over an extended range. These data are required for planning detailed human study. The RDI architecture has the potential for reuse of hardware and incurs significantly lower cost and risk than all other architectures that have been considered. The RDI architecture deserves further study and open discussion within the lunar science and engineering communities.

References: [1] D. J. Lawrence, et al. (2006) *JGR* 111, E08001, doi:10.1029/2005JE002637. [2] A. B., Sanin, et al., LPSC 38th (2007) #1648. [3] Garrick-Bethell, I. (2005) *Acta Astronautica* 57, 722-732.