A ROBOTIC PROSPECTING ARCHITECTURE FOR THE MOON. Paul D. Spudis, *Lunar and Planetary Institute*, Houston TX 77058 spudis@lpi.usra.edu

Introduction. The use of the resources of the Moon to create new space capabilities has been long considered, but only in recent years we have found the most critical resource (water) near the poles [1]. In addition, areas near both poles have been found that are in sunlight for significant fractions of the year [2,3], permitting sustained human presence on the Moon. These are exciting possibilities, but we remain ignorant of the quantities, locations and states of lunar water and of the environment and operating conditions of the polar locales. The acquisition of such knowledge is possible through the use of robotic spacecraft to map regional variations, local concentrations, and physical conditions of ice deposits. Although we have made some progress, detailed information for mineable quantities of water ice is needed.

Knowledge Needs. Although water exists in the polar regions, it is heterogeneously distributed and we are ignorant of its lateral and vertical distribution on km- and m-scales, its physical state(s), and the relation of ice deposits to local thermal and topographic conditions. We must also determine the nature of regolith in the permanently shadowed regions, in particular, mechanics properties such as soil density and trafficability. To access and harvest lunar water, we need to traverse the cold traps, acquire and manipulate ice-laden regolith, and process it into a relatively pure state. Models suggest that the near subsurface in partly lit areas may also contain ice [4], an important relation that must be confirmed. These activities require both mobility and manipulation of materials and we have no experience with such at the extremely low temperatures found in the polar areas.

Needed knowledge cannot be obtained from one technique, from a single observational location or from a single mission. We need new data from both orbit and the surface, using a variety of sensing techniques. Thus, although some of the currently planned robotic missions to the poles [5,6] will provide new and important information, they are inadequate to plan for large-scale harvesting and use of lunar water. In terrestrial mining, prospecting and ore assessment is a protracted and intensive process, in which detailed maps and operational plans are made, refined and tested. We must undertake a comparable campaign on the Moon to fully understand the nature of the prospect and its architectural implications.

Techniques and Missions. Different missions give unique perspective and data return. What additional information can be obtained from the various vantage points around and on the Moon?

Orbital missions. Existing orbital data are inadequate to address our strategic knowledge needs. Although we have complete monostatic radar coverage of the poles from orbit [7] and some bistatic data [8], we do not have complete bistatic coverage of the polar deposits. Bistatic radar can eliminate the ambiguity of radar CPR because ice and blocky surfaces have different responses to radar as a function of bistatic angle [8]. An instrument concept to obtain such data uses two identical instruments on two satellites to simultaneously map the poles of the Moon. The spacecraft would be placed in lunar orbit, physically joined to each other and map the poles over a lunar day. The two spacecraft would then separate into two, independently operated satellites to map the poles, gradually increasing their separation (and bistatic angle) over succeeding months to map the poles at bistatic angles between 1-12°. These images will give us maps of bistatic CPR in which ice and rock can be distinguished.

Neutron maps of polar hydrogen concentrations come from several missions, but such data have low resolution; higher resolution data could be obtained through the use of low altitude orbiters [9]. One technique provides both high resolution (~100 m) and precision (± 10 ppm) data – active neutron sensing from orbit. The Double Eagle concept [10] uses a neutral particle beam to illuminate small spots (few hundred meters) on the surface, which are then analyzed by sensors in orbit [11] (on the same or a different spacecraft). The production of such beam in space has been documented on a suborbital flight [12]. This mission could be conducted to provide prospecting data for hydrogen in the upper meter of polar soils.

Impactors and Hard Landers. LCROSS demonstrated that a collision on the Moon can excavate and expose volatile material to assess the presence and quantity of ice [13]. Additional impactors could provide more data points for promising areas, but as this approach requires considerable resources for a single data point, it is not a preferred method for prospecting. A swarm of hard-landing (i.e., tens of meters per second impact velocity) probes could provide multiple data points quickly and inexpensively. Each probe would be encased in a crushable shell to absorb the landing shock; the shell must be made of a hydrogen-free substance (e.g., aluminum foam). A small instrument package, such as a neutron spectrometer, could provide spot measurements of hydrogen. A bus of about 12 hard landers could be de-orbited with a solid rocket directly over a targeted shadowed area and then free-fall to the surface (a drop from 10 km would last 90 seconds and hit the Moon at approximately 150 m/s). These hard landers would be designed to survive for only a couple of hours; they would make their measurements, send them to the orbiter and die, producing a map of multiple data points for within the PSRs. Combined with other data sets, such a map would yield valuable insight into the distribution of polar water.

Fixed soft-landers. Soft-landing spacecraft offer the ability to make extended and sensitive measurements at a single locality. From such a mission, we could investigate surface and subsurface conditions, water amounts and determine geotechnical properties of polar regolith. Extended life landers can measure temporal phenomena, such as electrostatic charging of the surface. Each lander involves considerable expense, so it makes the most sense to use them carefully and sparingly. Fixed landers should be designed such that they could be accessed and used for parts by future lunar inhabitants. Commercial lunar landers also offer opportunities to obtain new data.

Rovers and Hoppers. Even with these new types of missions, we still need extended surface exploration with considerable mobility. Hoppers have the advantage of being able to reconnoiter distant, widely separated places of interest and are uniquely suited to investigate sites with different and variable potential (e.g., small craters on the floor of Peary; [7]). Rovers are able to traverse to interesting points, but can also characterize the terrain between such points, thus permitting the possibility of unsuspected and significant discoveries. Hoppers would be able to travel to only a few stations (probably less than 6), so landing sites must be considered carefully. A long-lived rover (preferably using an RTG for power) could be sent to investigate the most promising resource sites identified by other techniques. A rover can and should be equipped with considerable analytical capability, including the means to sample depths up to a couple of meters below the surface. Additionally, the rover must be equipped to evaluate trafficability and mechanical properties within and around potential prospects.

A Robotic Prospecting Architecture. We want to retire unknowns about the location and state of polar volatiles as expeditiously as possible. Thus, we first fly specially configured orbital missions to map the most promising areas for water mining. We are interested not only in the highest concentrations, but also the optimum locations – ice deposits must be accessible, have good trafficability to and from the mining sites, and be relatively close to power stations (sunlight) were processing will occur.

At least two new orbital measurements are needed: bistatic radar imaging will remove ambiguity from polar CPR measurements and determine prime locations for significant ice deposits. Two radar mapping spacecraft flown in tandem (ala GRAIL) can obtain these data within six months. Additionally, new neutron data for polar deposits are needed, with the highest resolution that we can obtain; a small orbital mission flown at close range can map the polar hydrogen at scales of 5-20 km. Ideally, active neutron sensing (e.g., Double Eagle mission concept) could produce a hydrogen map with resolution approaching ~100 m and precision of a few tens of ppm [10].

After these maps are obtained, a series of hard landers could be deployed to survey a site of high interest on the ground. A pallet of 12 hard landers can be de-orbited by a solid rocket motor and then scatter-deployed (e.g., spring-release mechanism) in order to free-fall to the surface over a wide area, impacting the Moon at 100-200 m/s. These probes should carry a small neutron spectrometer to measure promising areas and to ground truth the orbital neutron mapping data. The possible inclusion of additional instruments (e.g., XRF, imaging) should be investigated.

From these data, the most promising sites would be investigated from the ground by landers, some of which will deliver a surface rover. The lander is configured to study long-term environmental conditions, including thermal, electrical and plasma environments. The rovers contain a power system designed for long-life (trade between RTG and rechargeable fuel cell). They should conduct random walk traverses over prospects to map ice concentrations at meter- and cm-scales, laterally and vertically. Subsurface drill samples should be taken and analyzed. While in motion, the rovers make soil mechanics measurements to characterize the physical properties of polar regolith.

After these survey missions, a series of increasing more ambitious and sophisticated landers, rovers, and diggers should be sent to conduct ISRU tests, including demonstrations of excavation, processing, and product storage. All surface machines used on the Moon should be designed for maximum compatibility, including interchangeable parts and manipulation systems to enable remote teleoperated- and self-repair. From this series of missions, we will know where to begin our harvesting of lunar water, a game-changing technology that opens up the Moon and cislunar space to industrial development and permanent human presence [14].

References [1] Basilevsky A. *et al*. (2012) *Solar System Res.* **46**, 99. [2] Bussey B. *et al*. (1991) *GRL* **26**, 1187; (2005) *Nature* **432**, 842. [3] Mazarico E. *et al*. (2011) *Icarus* **211**, 1066. [4] Paige D. *et al*. (2010) *Science* **330**, 479. [5] Colaprete A. (2013) *LEAG Annual Mtg*., 7017 [6] Luna Resurs mission http://tinyurl.com/5sdao3b [7] Spudis P. *et al*. (2013) *JGR* **118**, 2016. [8] Patterson W. *et al*. (2015) *LPSC* **46**, 2888. [9] Lawrence D. *et al*. (2015) *Acta Astro*. **115**, 452. [10] Todd A. *et al*. (1994) *Proc. Intl. Linac Conf.* http://tinyurl.com/ov59xrh [11] Toefler A. *et al*. (1993) *LPI TR* **93-02**, 25. http://tinyurl.com/oppz7xe [12] O'Shea P. *et al*. (1990) *Proc. Intl. Linac Conf*., 739. http://tinyurl.com/olsf6jx [13] Colaprete A. *et al*. (2011) *Science* **330**, 463. [14] http://www.cislunarnext.org