Lunar PLANE: Lunar Polar Low-Altitude Neutron Experiment for High-Spatial Resolution Hydrogen Concentration and Depth Measurements. David J. Lawrence[1], Richard S. Miller[2], Patrick N. Peplowski[1], Martin Ozimek[1], Christopher Scott[1], [1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA (David.J.Lawrence@jhuapl.edu); [2]University of Alabama in Huntsville, Huntsville, AL, USA.

Introduction: Permanently shaded regions (PSRs) are fascinating solar system environments. The type locations for PSRs are craters located at both poles of the Moon and Mercury. The interiors of these craters are not illuminated by sunlight and consequently their temperatures are very cold (T<100K) for geologically long periods of time. One of the most important aspects of PSRs is that they serve as cold traps for volatiles (e.g., water). Predictions dating back to the 1960s and 1970s proposed that lunar PSRs would have enhanced water concentrations [1,2]. Subsequent spacecraft and Earth-based measurements using various techniques (radar, neutron spectroscopy, spectral reflectance) have provided abundant evidence to support these predictions at both the Moon and Mercury [e.g., 3-7]. The characteristics of these regions and the processes that take place in PSRs have implications for a variety of topics such as the origin and history of solar system volatiles [8], synthesis of organic materials [9], and in-situ resources for human exploration.

Despite the fact that initial measurements of PSRs have been made, many aspects of PSRs are not known or understood. In particular, our knowledge of the spatial distribution and depth dependence of hydrogen concentrations at the lunar poles is tantalizingly incomplete. The topic of this study is to investigate the extent to which a low-cost, low-resource orbital mission can achieve significant improvements in our knowledge of the lunar polar hydrogen distribution. A better knowledge of the polar hydrogen spatial and depth distribution will have multiple benefits as it can provide key input to studies of PSR volatile processes by isolating individual craters that host enhanced hydrogen. In addition, data from such a mission will be valuable for future landed missions that seek to target landing sites with volatile enhancements [10].

Hydrogen Measurements of Planetary Surfaces: Planetary neutron spectroscopy is the standard technique for quantifying hydrogen concentrations on planetary surfaces [11]. Neutrons are created by nuclear spallation reactions when high-energy cosmic rays strike the surface of an airless or nearly airless planetary body. The energies (E_n) of the resulting neutrons are typically divided into three ranges of fast (E_n > 0.5 MeV), epithermal (0.5 eV < E_n < 0.5 MeV) and thermal (E_n < 0.5 eV) neutrons. Hydrogen has a unique ability to moderate neutrons because hydrogen atoms and neutrons have the same mass, which allows a highly efficient momentum transfer between the two. This causes the number of epithermal neutrons to be strongly depressed where hydrogen is present so that epithermal neutrons can provide a highly sensitive measure of a soil's hydrogen content. Fast neutrons are also sensitive to the hydrogen content in a planetary soil, but because their effective penetration depth differs from that of epithermal neutrons, fast neutrons also provide information about the burial depth of hydrogen enhancments [7,12].

Polar hydrogen enhancements were first measured on the Moon using the Lunar Prospector Neutron Spectrometer (LP-NS)[3]. The LP-NS was an omnidirectional detector and as a consequence its spatial resolution was sufficiently broad that individual hydrogen enhancements were generally not tied to specific PSRs. Nevertheless, combined measurements of epithermal and fast neutrons have been used to show that bulk hydrogen enhancements in Shackleton crater at the Moon's south pole reach to the surface [12], in contrast to other polar regions where the hydrogen enhancements are likely buried by tens of cm of dry soil [13].

To obtain higher spatial resolution measurements, the Lunar Reconnaissance Orbiter spacecraft carried a collimated neutron detector known as the Lunar Exploration Neutron Detector (LEND)[14], which was planned to quantify hydrogen concentrations at a spatial resolution of 10 km near both lunar poles. Despite reports that claim the LEND instrument has met its spatial resolution requirements [15-17], multiple studies have shown that the collimated neutron data have not successfully made hydrogen concentration measurements with 10 km spatial resolution [18-22]. In contrast to collimating neutrons, if a mission can be designed where the altitude over one of the poles is significantly lower than that of the LP-NS measurements, then omnidirectional neutron measurements should improve the spatial resolution roughly by the ratio of the respective altitudes.

Lunar PLANE Mission: The Lunar Polar Low-Altitude Neutron Experiment (PLANE) can be accomplished with simple neutron sensors on a small spacecraft. The most easily accomplished mission obtains high-spatial-resolution hydrogen concentrations with a single ^{3}He neutron sensor on a CubeSat-like spacecraft. To obtain spatially-resolved depth-dependent hydrogen concentrations, a fast neutron sensor needs to be included in the mission payload. High heritage fast neutron sensors are available for a few kg mass [23].

The nominal mission scenario provides for low-altitude (<25 km) passes over the lunar south pole with higher-altitude apoapsis (~200 km) values to provide orbital stability. To calculate the mission orbit, an order 50x50 lunar gravity model was used and Earth and Sun perturbations were included. Figure 1 shows histograms of the south-pole altitudes for the Lunar PLANE and LP missions. The LP mission shows a wide spread of higher altitudes, which results in a relatively broad spatial resolution. In contrast, the Lunar PLANE mission has both lower altitudes and a narrower altitude spread, which will result in improved neutron spatial resolution.

To assess the utility of the Lunar PLANE mission to obtain spatially resolved hydrogen measurements, we used the spatially-reconstructed neutron count rate map of Teodoro et al. [22] as an assumed ground truth (Figure 2). To simulate the neutron measurements for the Lunar PLANE mission scenario, we use neutron transport simulations that have been validated for prior planetary missions [7]. Figure 3 shows the simulated count rate map when the distribution of Figure 2 is used as an assumed count rate distribution. As seen, all of the largest PSRs are spatially resolved. This is in contrast to the measured LP-NS data that show a much broader spatial resolution (Figure 4).

The next step to assess the mission viability is to assign variable burial depths for different PSRs and investigate how well a Lunar PLANE mission could measure such burial depths. This analysis will be accomplished using the known response properties for a standard fast neutron detector [7].

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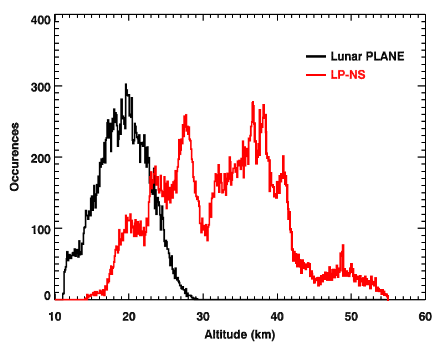

Fig. 1. Altitude histograms for the Lunar PLANE and Lunar Prospector missions for latitudes poleward of 70ºS.

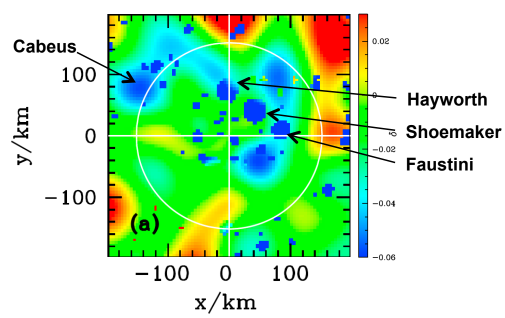

Fig. 2. Spatially-reconstructed epithermal neutron count rates for the lunar South Pole based on analysis of [22]. Prominent PSRs are labeled.

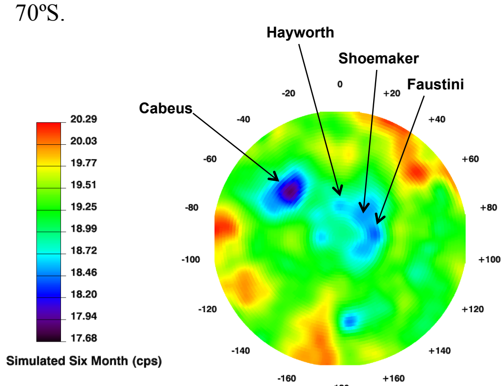

Fig. 3. Simulated epithermal neutron count rate map at the lunar South Pole for the Lunar PLANE mission.

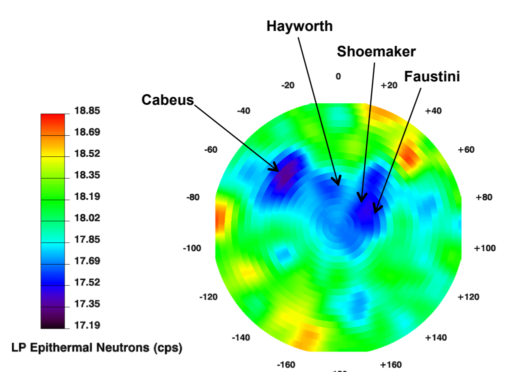

Fig. 4. Measured LP-NS epithermal neutron count rate map for the same projection as Fig. 3.