



# High-resolution mapping of lunar polar hydrogen with a low-resource orbital mission

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## ABSTRACT

Lunar permanently shaded regions (PSRs) are unique solar-system environments. Their low temperatures ( $< 100$  K) facilitate cold trapping of volatile materials over timescales comparable to the lifetime of the solar system. While much has been learned about these regions from orbital spacecraft, important missing information includes the spatial and depth-dependent distribution of bulk hydrogen concentrations in and around PSRs. We present two complementary mission scenarios where orbital neutron spectroscopy will provide significantly improved understanding of lunar polar bulk hydrogen concentrations. In the first mission concept, a six-month orbital mission will measure bulk hydrogen concentrations with sensitivity better than 50 ppm and a spatial resolution of order 20 km over the entire lunar South Polar region (poleward of  $80^{\circ}$ S). Spatial reconstruction analyses of the returned data will improve the final spatial resolution to better than 10 km. The presence and burial depth ( $< 25$  cm) of subsurface deposits will be quantified with latitude-dependent sensitivities ranging from 50 to 350 ppm. The second concept envisions a few, very low altitude ( $\sim 5$  km) flyovers of one or more PSRs to quantify the hydrogen concentrations and spatial heterogeneities with a hydrogen sensitivity less than 200 and spatial scale size of 5 km. Both concepts can be combined in a single mission where full-coverage polar measurements are made with a hydrogen spatial resolution of 20 km, and higher spatial resolution measurements are made for a few strategically selected PSRs at the end of the mission.

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## 1. Introduction

Permanently shaded regions (PSRs) are unique and 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 directly illuminated by sunlight and consequently maintain temperatures  $< 100$  K for geologically long periods of time.

One of the most important aspects of PSRs is that they serve as cold traps for volatiles, including 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 [3–7]. The characteristics of PSRs and the processes that take place within them have implications for a variety of topics such as the origin and history of solar

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system volatiles [8], synthesis of organic materials [9], and in-situ resources for human exploration.

Despite being the subject of intensive Earth and spacecraft based observations, many aspects of PSRs remain a mystery. Observations at Mercury show that there are significant amounts of water ice and other volatiles that are closely correlated with spatial and depth locations of volatile thermal stability [6,7,10–12]. In contrast, the spatial distribution and depth dependence of lunar polar hydrogen concentrations are not well correlated with locations of volatile thermal stability. For example, while surface frost has been observed in most lunar PSRs [13], bulk hydrogen concentrations do not appear to be uniformly enhanced within PSRs [14,15], and are not well correlated with locations of volatile stability expected by surface and subsurface temperatures in polar regions [16]. This qualitative difference between the lunar and mercurian PSRs, despite their similar environmental conditions (e.g., temperature, temporal stability), is not understood. Possible reasons for this Moon/Mercury PSR discrepancy are likely related to various volatile retention/removal processes, as well as volatile delivery sources and mechanisms.

Improved knowledge of the spatial and depth distribution of hydrogen concentrations would significantly advance our understanding of the processes and delivery sources. Specifically, the spatial distribution of hydrogen concentrations needs to be known at a spatial scale that is at least as small as the PSRs themselves. Such data could help determine if the source delivery mechanisms have occurred over a long time scale (e.g., via solar wind) and/or if volatiles were delivered through episodic events like cometary impact(s) [17]. Knowledge of the hydrogen concentration inside and outside PSRs will provide observational constraints to understand what environmental effects (e.g., surface and/or subsurface temperature) are strongly related to the current hydrogen distribution. Knowledge of the hydrogen burial to depths of tens of cm at a similar spatial scale can provide additional key constraints on various delivery and retention processes and time scales [18].

One of the best techniques for remotely measuring bulk hydrogen concentrations on planetary surfaces is neutron spectroscopy. Neutron spectroscopy is highly sensitive to low hydrogen concentrations, and is therefore well suited for making such measurements at the Moon. While various attempts have been made to improve our knowledge of the hydrogen spatial distribution on the Moon (e.g., [14,15,19]), there remain significant uncertainties regarding the spatial distribution at scales of < 50 km (e.g., [20–23]). In addition, very little is known about hydrogen burial within PSRs except broad burial depth limits [24] and some spatial information of burial depths near the Moon's South Pole [18].

The topic of this study is to present two variants of a low-resource orbital mission concept that 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 provide key input to studies of PSR volatile processes by isolating individual craters that host enhanced hydrogen concentrations. In addition, data from such a mission will be

valuable for future landed missions that seek to target landing sites with volatile enhancements [25].

## 2. Planetary neutron spectroscopy and lunar polar hydrogen measurements

Planetary neutron spectroscopy is the standard technique for quantifying hydrogen concentrations on planetary surfaces [26]. 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 is uniquely suited for moderating neutrons due to its comparable mass, which allows a highly efficient momentum transfer during elastic collisions. This causes the number of epithermal neutrons to be strongly reduced where hydrogen is present, such that epithermal neutron flux measurements provide a highly sensitive measure of a soil's hydrogen content. Fast-neutron fluxes are also sensitive to the hydrogen content in a planetary soil, but because their effective penetration depth differs from that of epithermal neutrons, comparisons of fast and epithermal neutron measurements can provide information about the burial depth of hydrogen enhancements [7,18].

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 whose spatial resolution of  $\sim 45$  km (obtained at an altitude of 30 km; [27]) was sufficiently broad that hydrogen enhancements within specific PSRs could not be resolved. Nevertheless, Lunar Prospector (LP) measurements of epithermal and fast neutrons have been used to show that bulk hydrogen enhancements in Shackleton crater at the Moon's south pole likely reach to the surface [18], which is in contrast to other polar regions where the hydrogen enhancements are likely buried by tens of cm of drier material [24].

Higher spatial resolution information was obtained from LP-NS data using spatial reconstruction analyses. These analyses remove the smoothing effects of the LP-NS spatial response to the limits allowed by the statistical uncertainties of the data [14,19,28]. These types of spatial reconstruction analyses have been conducted with a variety of datasets, including astrophysical observations [29], as well as other planetary neutron and gamma-ray measurements of Mars and the Moon [30,31]. For the lunar polar neutron data, an additional physical constraint – the amount of allowed hydrogen as a function of permanent shade – was coupled to the reconstruction analyses to provide more robust and physically reasonable results. These studies demonstrated that the measured LP-NS data are consistent with a hypothesis in which hydrogen is enhanced in some PSRs, but not uniformly across all PSRs [14,19,28].

To obtain higher spatial resolution measurements, the Lunar Reconnaissance Orbiter spacecraft carried a collimated neutron detector known as the Lunar Exploration Neutron Detector (LEND), which had the goal of quantifying hydrogen concentrations at a spatial resolution

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